T SOIL PHYSICAL FACTORS

AFFECTING ROOT GROWTH AND MAIZE YIELD

IN FOUR RHODESIAN SOILS

A
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DECLARATION

In the execution of the research reported in this thesis, specific assistance, other than from my Supervisor, has been received from:

Professor A.E. Erickson who supplied the platinum microelectrodes;

Mr. G.J. Wilson who designed the field penetrometer;

Mr. J. Chadwick who made the laboratory penetrometer needles;

Mr. M.F. Franklin who gave advice on the statistical analysis of some of the data;

Dr. H.M. Taylor and Dr. B. Cockroft who supplied basic data from some of their publications;

Officers of the Departments of Research and Specialist Services and of Conservation and Extension of the Rhodesian Ministry of Agriculture who were responsible for the planning and execution of the tillage trials at Domboshawa, Grasslands, Makoholi and Hatcliffe;

Messrs. W.D. Chikodzore and S.C. Munyaradzi who gave technical help in connection with undisturbed core sampling, laboratory measurements of soil physical factors, collection of field penetrometer data and extraction of root profiles from the tillage trials.

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ABSTRACT

The platinum microelectrode technique for measuring oxygen flux in soils has been reviewed. Shortcomings in the existing technique and instrumentation have been discussed. The new instrumentation, electrode standardization and measurement techniques developed enable the method to be used with confidence in unsaturated soil systems. Measurements of oxygen flux index in four soil samples showed a very highly significant regression relationship between oxygen flux index and air space within the range 3 - 15% air space on each soil. There was no significant difference in the regression relation between soils.

A field penetrometer, designed to measure the presence and strength of subsurface pans in field soils has been described. Measurements with the penetrometer on three depth of ploughing treatments (100, 230 and 355 mm) on tillage trials at four sites with different clay contents showed that hard layers were present on all the treatments. Except on the shallowest ploughing depth treatment on the fine-textured soil, where the pan was 225 mm below the nominal ploughing depth, the hard layers were present between a few mm and 150 mm below the nominal ploughing depth, and had strengths of between 16 and 24 bars.

The theory and factors affecting measurement of soil strength with needle penetrometers have been investigated. The design and operation of a laboratory penetrometer used to measure soil strength under closely controlled laboratory conditions has been discussed.

Physical factors likely to affect root growth, viz. soil texture, air space, bulk density, soil strength and available moisture, have been measured in a comprehensive range of undisturbed cores taken from the four tillage trials. High soil strength is considered as being the soil physical factor most likely to restrict root growth in these soils. Physical factors affecting soil strength have been investigated. Soil strength is shown to be highly dependent upon bulk density,

matric potential and soil texture.

The hard pans shown to exist in all the tillage trial soils exhibit many of the characteristics of tillage pans, but their existence cannot be attributed exclusively to the ploughing depth treatments imposed in the tillage trials. Rather, the pans have resulted from a combination of interacting factors, including the previous history of the soils, the imposed tillage treatments, crop, and climatic factors.

A study of some of the data from the literature on root growth and soil strength shows that root growth is severely restricted by soil strengths of the order of 20 to 30 bars. In order to determine whether root growth was being restricted in the tillage trials, root profiles were extracted from one of the trials. These showed that the pans severely restricted root growth.

Analysis of maize yield data from the tillage trials showed that on the three coarse-textured sites yield increased with increased depth of ploughing, and that there was a marked seasonal effect, ploughing depth having a relatively greater effect on maize yield in dry seasons than in wet. On the fine-textured site, however, where no pan existed near the surface in the shallow ploughed treatment, the ploughing depth effect was not significant, nor was there any marked seasonal effect of ploughing depth on maize yield. Evidence presented shows that the pans, by restricting root growth are reducing the amount of water available to the plant. This effect is greater in dry seasons, and in soils with low available water.

INTRODUCTION

Fifteen years ago very little was known about the effect of deep ploughing on Rhodesian soils. It was widely believed, but there was very little concrete evidence, that deep ploughin would be advantageous on many granite sands. There was also some evidence that yields in African areas were limited by poor and shallow ploughing.

In order to study the effect of depth of ploughing on maize yield in granite sand soils, a series of three tillage trials was initiated in 1965 by staff of the Departments of Research and Specialist Services and of Conservation and Extension. These trials set out to examine the effects of ploughing continuously to 100, 230 and 355 mm with two types of plough, viz. mouldboard and disc, on maize yield. Furthermore, because of the low inherent fertility of these granite sand soils it was thought that better use could be made of compost if it were ploughed in deeply, so three levels of compost were applied as sub-plots of the main treatments. In a fourth trial started in 1968 the compost treatments were replaced by three levels of fertilizer plus lime.

The initial three tillage trials were at Domboshawa Training School (near Salisbury), Grasslands Research Station (near Marandellas) and Makoholi Experiment Station (near Fort Victoria). The trial sites were on para-ferrallitic soils derived from granite. Thompson (1965) describes the soils of this group as ranging from highly porous coarse-grained sands throughout the profile, to similar sandy loams over yellowish-red sandy clay loams. The clay fractions consist almost entirely of kaolinite and amorphous sesquioxides of iron and aluminium, with appreciable reserves of weatherable minerals.

The fourth tillage trial was at Hatcliffe Agricultural Engineering Centre (near Salisbury) on a fine-textured red fersiallitic soil derived from banded ironstone. Thompson (1965) describes these soils as being red clays with pronounced crumb or granular micro-structure. The clay fraction is

mainly kaolinite, with some 2:1 lattice minerals, appreciable amounts of free sesquioxides of iron and aluminium, and appreciable reserves of weatherable minerals.

The approximate distribution of the para-ferrallitic and para-ferrallitic/fersiallitic granite-derived soil group associations are shown overleaf, together with the locations of the four trial sites. Soils of the type at Hatcliffe occur widely, but seldom occupy extensive areas (Vincent and Thomas, 1961), so it is not practicable to represent them on a small-scale map.

Early results from the trials, reported by Grant (1968), indicated that depth of ploughing strongly influenced distribution of roots. Shallow ploughing resulted in a large proportion of the roots being concentrated near the surface, whereas with deeper ploughing the roots were more evenly distributed. There was also some evidence of maize yields being lower on the shallow ploughed treatments.

The trials proper ran for a period of seven years, and the objectives of the investigations undertaken in this thesis were:

1) to evaluate the effect of imposed treatments on soil physical parameters,
2) to establish which physical factor or factors were restricting root growth, and
3) to determine the effects of these physical factors on root growth and maize yield.

Soil physical parameters considered most likely to influence root growth and maize yield in these soils were soil aeration, soil strength and available moisture. Techniques chosen to be the most suitable for measuring these three physical parameters were:

1) soil aeration - measurement of oxygen flux using the platinum microelectrode,
2) soil strength - resistance to penetration with the penetrometer, and
3) available moisture - measured as the difference

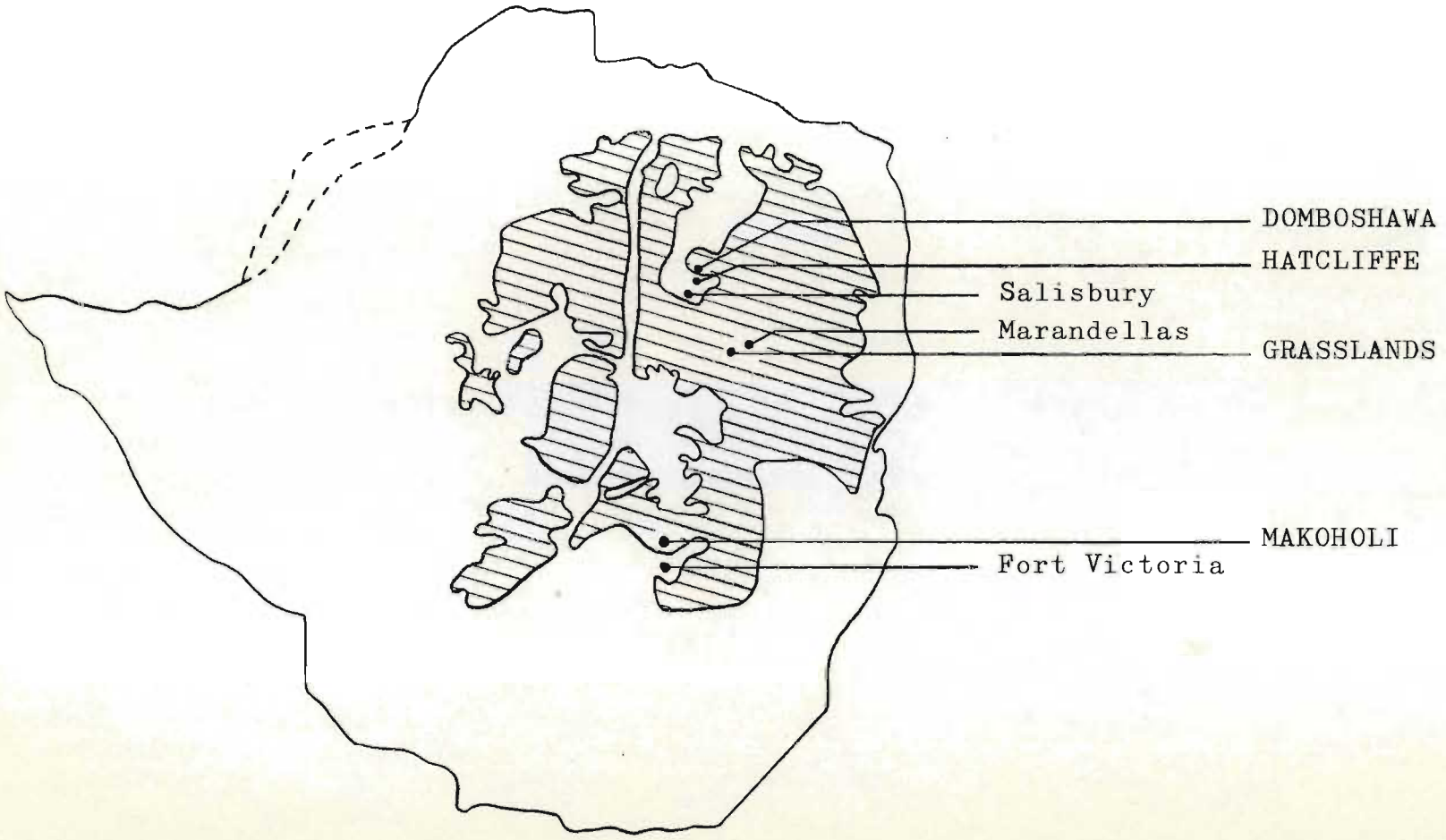


Fig. A Map of Rhodesia showing approximate distribution of granite-derived para-ferrallitic soils and locations of the Domboshawa, Grasslands, Makoholi and Hatcliffe tillage trial sites (drawn from Thompson, 1965)

between water held at 'field capacity' and -5 bars matric potential.

Considerable problems were experienced at the outset with the platinum microelectrode technique for measuring oxygen flux, and it was decided to digress from the original objectives and investigate the technique fully with a view to improving it. The theory of operation of the platinum microelectrode in saturated and unsaturated systems was therefore investigated fully and new instrumentation and methodology developed for measuring oxygen flux in unsaturated soils is described.

Similarly, the theory of needle penetrometers was studied, and a penetrometer designed to measure soil strength under carefully-controlled laboratory conditions is described. A field penetrometer designed to measure soil strength in field soils is also described.

In order to evaluate the physical characteristics of the tillage trial soils a comprehensive range of undisturbed cores was taken from the four tillage trials. These cores were subjected to extensive physical measurements, viz. particle size distribution, bulk density, soil strength at 'field capacity' and -1 000 mbar matric potential, air space at -20, -50 and -100 mbar matric potential, and available soil moisture. These measurements, together with measurements with the field penetrometer showed that high soil strength zones existed in all the tillage trials at various depths below the nominal plough depth.

In order to establish whether high soil strength was affecting root growth in the trials studied, two different lines of approach were made. Firstly, root growth/soil strength data obtained from the literature were studied in order to establish approximate 'critical' soil strengths at which root growth was stopped. These calculated values were then compared with the soil strength values obtained in this investigation with the field and laboratory penetrometers. Secondly, root profiles were extracted from the three depths of ploughing so that the extent of the root system under field

conditions could be determined.

The ultimate objective of the investigations conducted in this thesis was to determine the effects of the soil physical factors on maize yield. Evaluation of the physical factor or factors restricting maize yield should help to improve management practices, and maximize the potential of these soils.

CHAPTER 1

THEORY OF OXYGEN FLUX MEASUREMENT

1.1 Introduction

The platinum microelectrode technique for measuring oxygen flux in soils is a development of a method of chemical analysis, termed polarography, evolved by Jaraslov Heyrovsky in 1922. The method is based on the unique characteristics of the current voltage curves obtained when solutions of electro-oxidizable or electroreducible substances are electrolysed (Kolthoff and Lingane, 1952). The technique was first used in biological systems by Davies and Brink (1942) who measured oxygen in animal tissue. Lemon and Erickson (1952) introduced the method to the field of soil science, using the platinum microelectrode for measuring oxygen flux (traditionally but incorrectly called oxygen diffusion rate, or ODR, McIntyre, 1970) in soils.

In use an external potential is applied between a platinum microelectrode (cathode) and a large nonpolarizable reference electrode (saturated calomel or silver/silver chloride) as anode. The basic circuit diagram is shown in Fig. 1.1. Oxygen is reduced at the platinum cathode and an electric current (measured on the microammeter) flows. The current flowing is proportional to the rate of oxygen reduction. A characteristic current-voltage relation for a saturated system is shown in Fig. 1.2. Current flow due to oxygen reduction begins at about -0,2 V and increases as potential decreases. The current resulting from this reaction gradually approaches a limiting value and becomes nearly constant and independent of further decreases in applied potential. When the applied potential is decreased below about -0,8 V, however, the current rises sharply. This rise is due to another reaction, the reduction of hydrogen ion to hydrogen gas.

On the plateau region, where a limiting current is reached, oxygen is reduced as rapidly as it reaches the electrode surface. The concentration of oxygen at the electrode surface remains constant at a value that is negligibly small compared to that

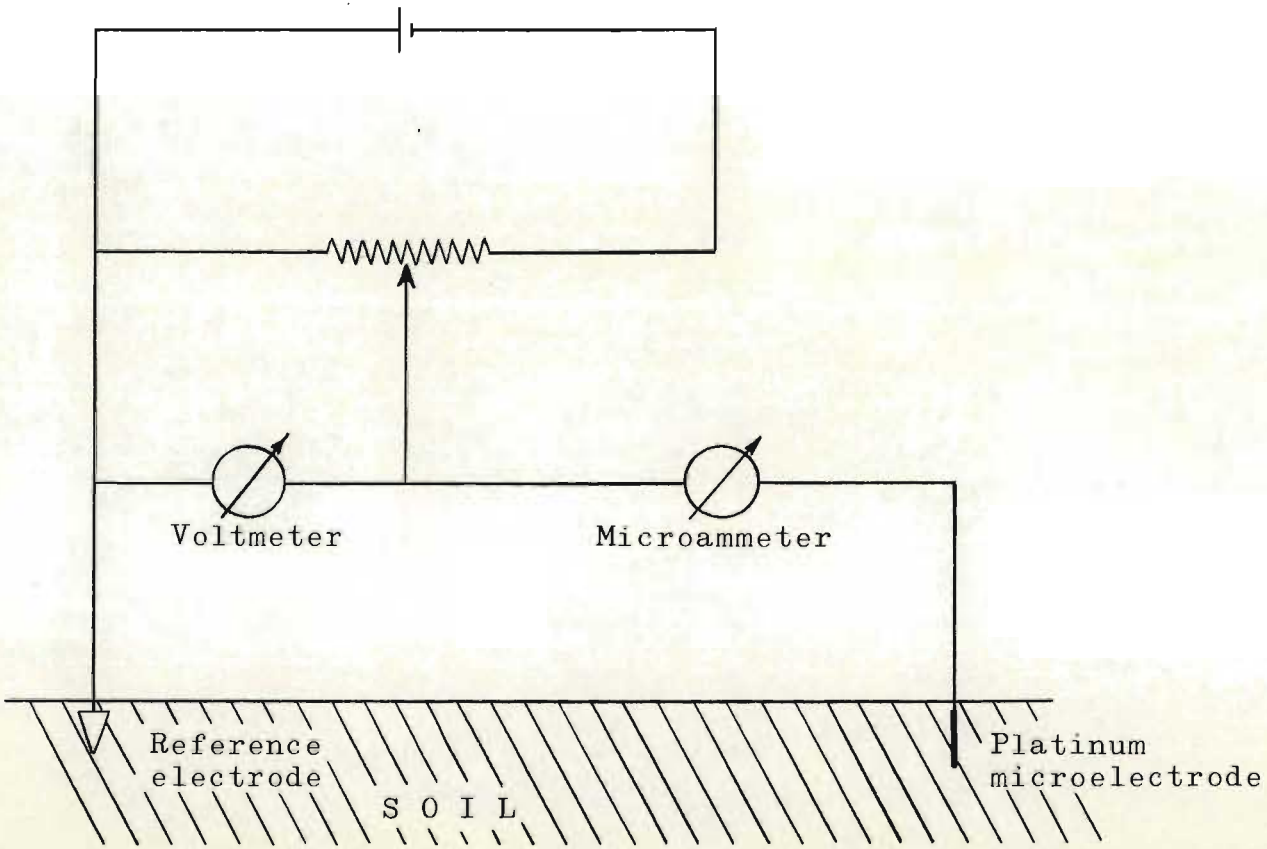


Fig. 1.1 Simplified circuit diagram for the measurement of oxygen flux

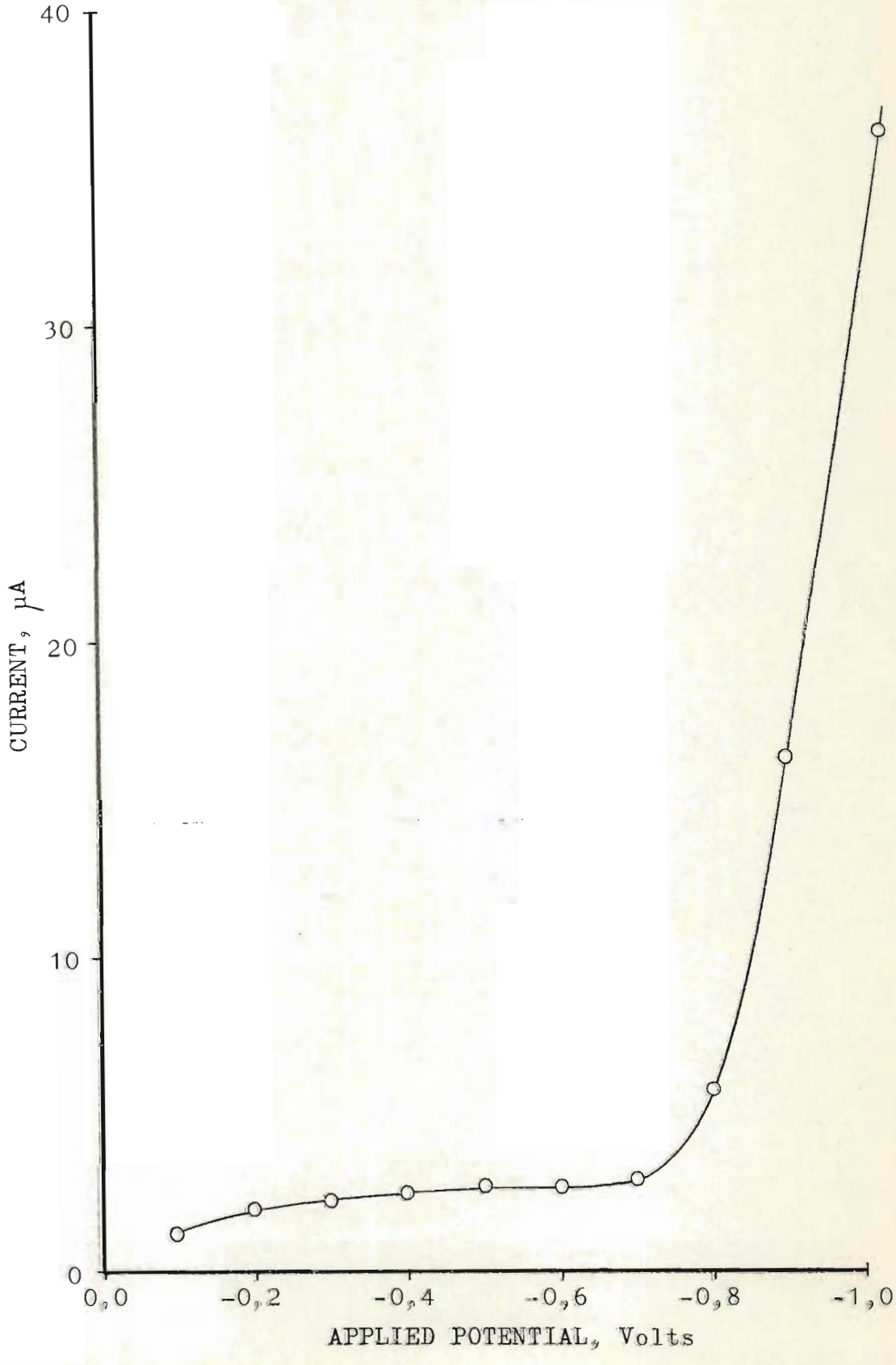


Fig. 1.2 Current-voltage curve for a 3% clay suspension in 0,1N KCl

in the body of the solution. Under these conditions, the current resulting from the reduction of oxygen at the platinum surface is governed solely by the rate at which oxygen diffuses to the electrode surface from the surrounding medium (Kolthoff and Lingane, 1952).

Fick's law of diffusion is applicable to this case and has been successfully applied by Laitinen and Kolthoff (1941). Thus, using Fick's law of diffusion for a linear system, oxygen flux is related to the concentration gradient of oxygen by

$$f_{a,t} = D \left(\frac{\delta c}{\delta x}\right)_{a,t} \qquad 1.1$$

where $f_{a,t}$ = oxygen flux at time t at the surface of an electrod of radius a; D = the effective diffusion coefficient for oxyge in the solution, and c = oxygen concentration in the solution.

Letey and Stolzy (1964) considered that a cylindrical co-ordinate system was more appropriate than a linear system fo the platinum microelectrode. The general steady state diffusi in cylindrical co-ordinates is

$$\frac{\delta^2 c}{\delta r^2} + \frac{\delta c}{r \delta r} = 0 \qquad 1.2$$

The boundary conditions associated with the electrode are C_b = oxygen concentration at radius b, and C_a = oxygen concentration at the electrode surface, radius a. Integration of equation 1.2 with these boundary conditions leads to

$$\frac{\delta c}{\delta r} = \frac{(C_b - C_a)}{a \ln(b/a)} \qquad 1.3$$

The flux is a product of the diffusion coefficient and the concentration gradient (equation 1.1), so

$$f_{a,t} = \frac{D(C_b - C_a)}{a \ln(b/a)} \qquad 1.4$$

In soil systems it is assumed that a liquid film of mean thickness (b - a) separates the electrode from the gas phase. The thickness of this film, called 'the apparent mean liquid

path length' (Kristensen and Lemon, 1964) and 'mean film thickness' (Letey and Stolzy, 1967) will depend on the moisture content of the soil. In operation it is assumed that C_b is the equilibrium oxygen concentration in solution for the particular partial pressure of oxygen in the gas phase, and $C_a = 0$. Putting $(b - a) = \delta r$, equation 1.4 is then written

$$f_{a,t} = \frac{DC_b}{a \ln(1 + \delta r/a)} \qquad 1.5$$

Figure 1.3 depicts the model used to explain electrode behaviour on the basis of equation 1.5. This model is considered to represent soil conditions near a root, or the microelectrode in unsaturated soil (Kristensen and Lemon, 1964).

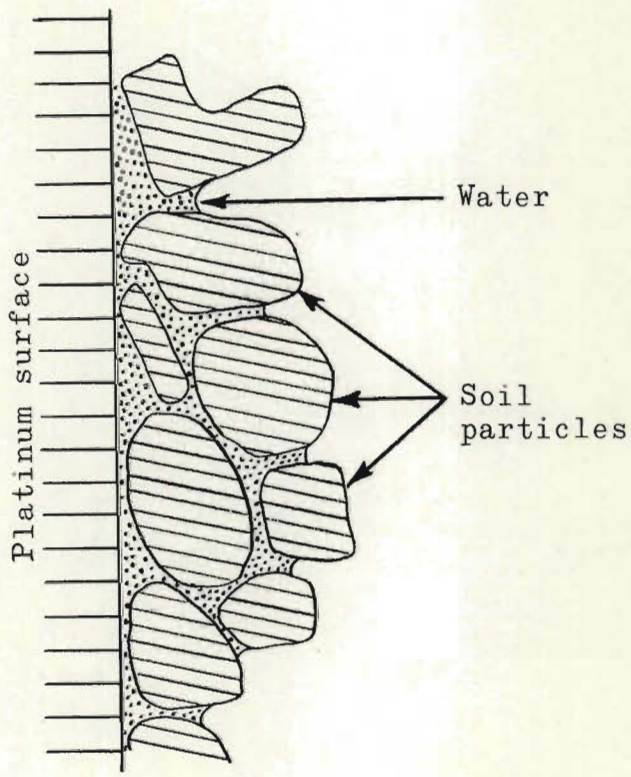
Oxygen flux measured in the first instance as a current, is converted to the more meaningful units of amount of oxygen reduced per unit electrode area per unit time, using the working equation

$$f_{a,t} = \frac{Mi_t}{nFA} \quad \mu g\ m^{-2}\ s^{-1} \qquad 1.6$$

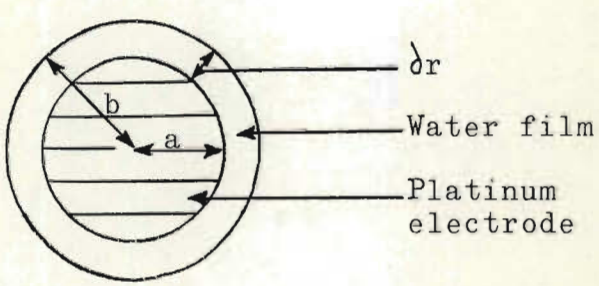
where $f_{a,t}$ = oxygen flux at time t at the surface of an electrode of radius a; i_t = current in microamps at time t; M = molecular mass of oxygen (= 32 g $mole^{-1}$); n = number of equivalents per mole of oxygen (= 4); F = the Faraday (96 500 coulomb g $equiv.^{-1}$), and A = area of electrode in m^2.

Current readings are generally taken after attainment of a quasi-stationary state, four to five minutes after application of potential to the electrode system. Figure 1.4 shows current-time curves obtained in two saturated systems. These show that after three minutes the decrease in current with time is minimal. Readings are generally taken after four minutes.

In two-phase systems current is controlled purely by the rate of diffusion of oxygen to the electrode surface. Current is independent of applied potential in the plateau region (-0,2 to -0,7 V) in saturated (Fig. 1.2) or near-saturated (Fig. 1.5) systems and the diffusion model described explains microelectrode behaviour. Consideration will now be given



(a)



(b)

Fig. 1.3 Diffusion model to explain microelectrode behaviour: (a) Particles and solution separating the electrode from gas-filled pores, and (b) Coaxial cylindrical model with water film of mean thickness δr separatir the electrode from gas-filled pores (after Kristense and Lemon, 1964)

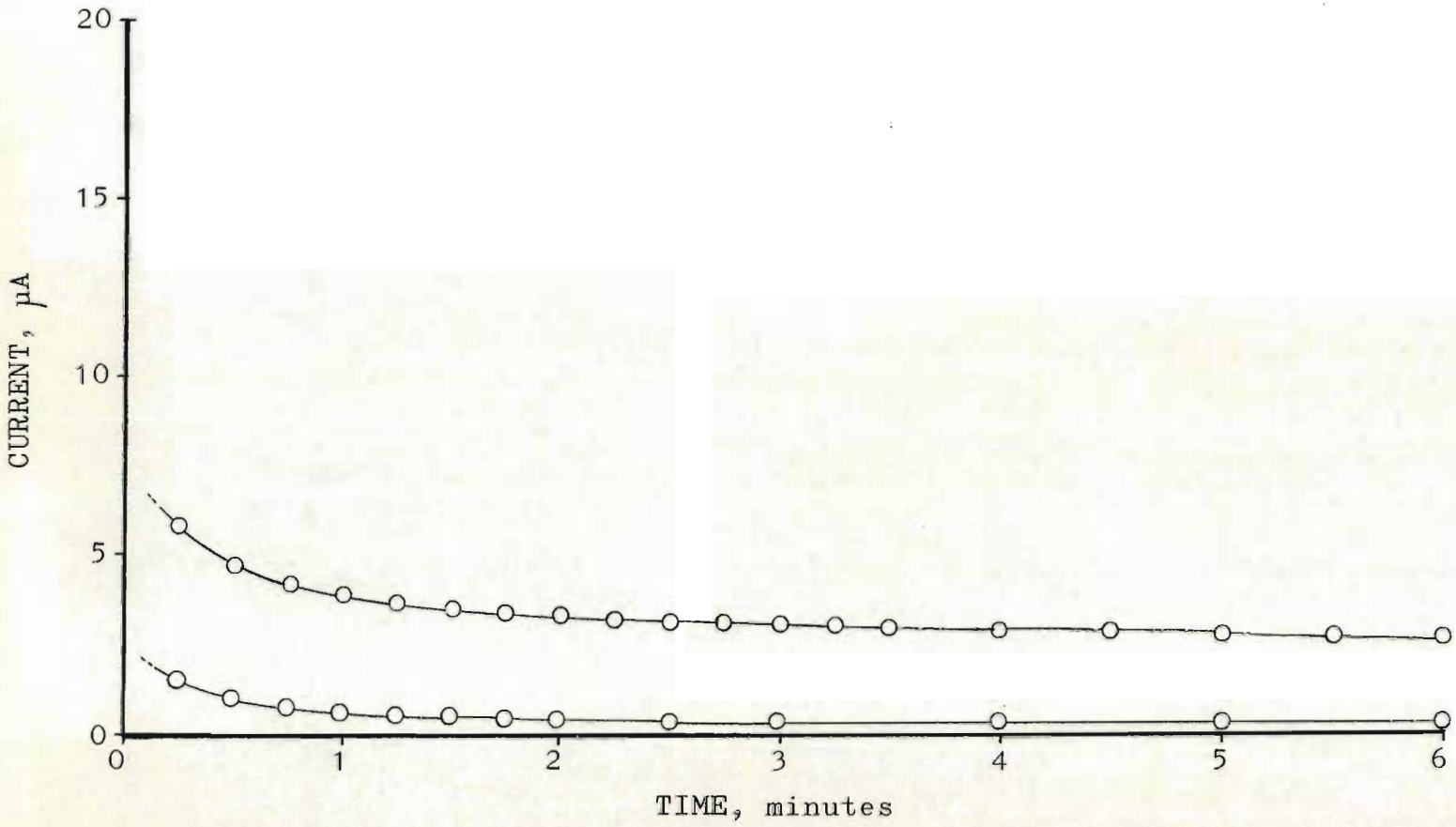


Fig. 1.4 Current-time curves for two saturated media

to the unsaturated (soil-water-air) system.

1.2 Platinum microelectrode operation in unsaturated systems

In two-phase media diffusion rate of oxygen has an overwhelming influence on current limitation. For three-phase media it has often been tacitly assumed that the response is similarly governed. Current-voltage curves at a range of moistures in a sand will show the effect of desaturation (air entry) on diffusion control of current at the platinum microelectrode.

a) Materials and methods

One kilogram of a bulk sample of silica sand ($< 0,5$ mm) which had been washed and dried, was poured into each of six rigid PVC cylinders. The bottom end of the cylinder was closed with a circle of cloth held in place by a rubber band. The cylinders were 100 mm high and had an internal diameter of 100 mm. The bulk density of packing was 1,61 g cm^{-3}. The cylinders containing sand were placed on a tension tray and saturated with 0,1N KCl (see section 2.5.1 for explanation of this).

Current measurements were made at 0,1 V decrements from -0,1 to -1,0 V with a new electrode position being used for each measurement. One cylinder was used at each matric potential; saturation, 0, -20, -40, and -60 mbar; matric potentials being measured with reference to the bottom of the cylinders. The sixth cylinder was used for the silver/silver chloride reference electrode.

b) Results and discussion

Current-voltage curves for the sand at different matric potentials are shown in Fig. 1.5. The curves show that the plateau disappears at an early stage of desaturation, and that once the plateau has disappeared the curves become quite steep. The curves shown are similar to those obtained by Kristensen

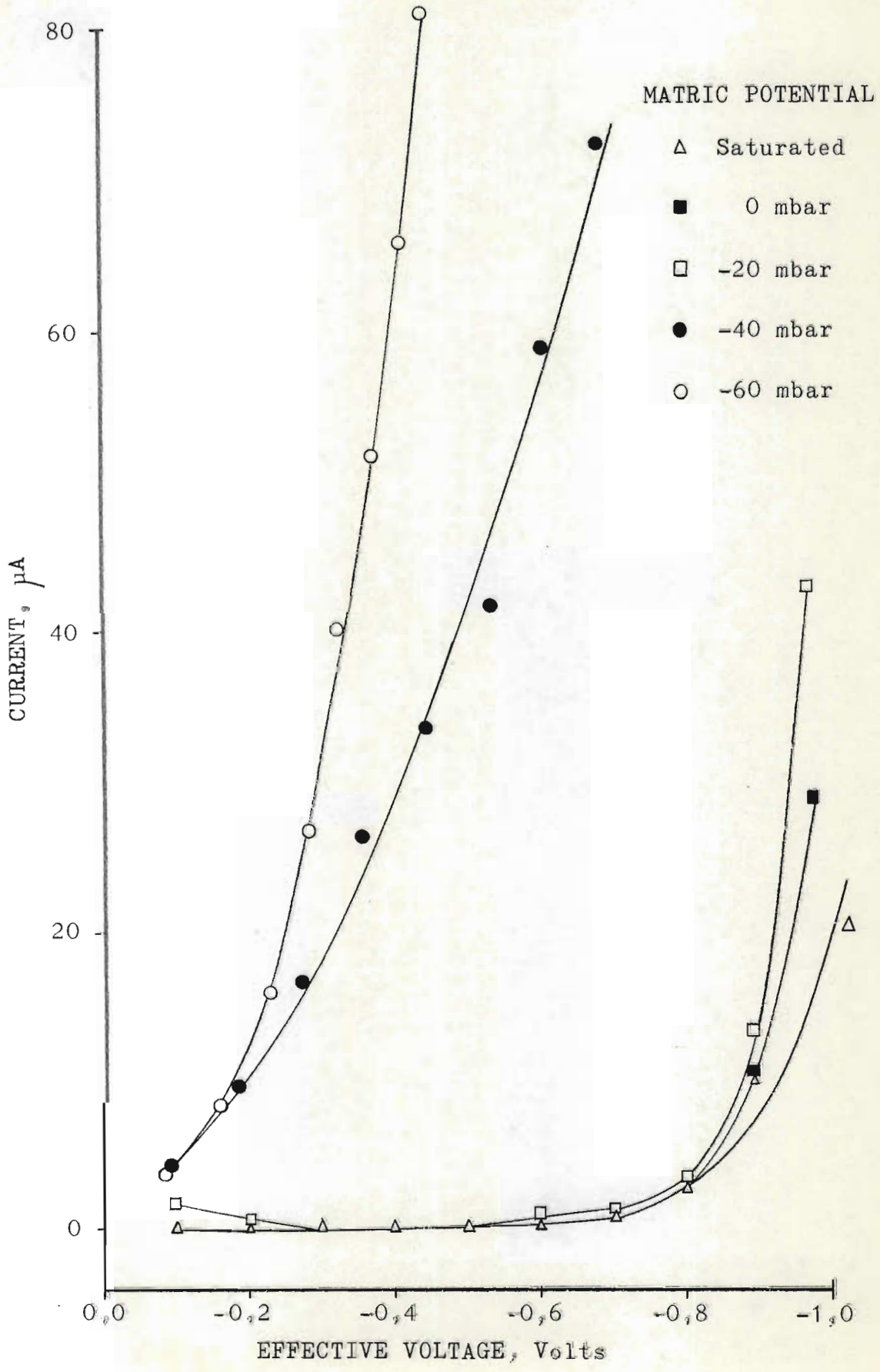


Fig. 1.5 Current-voltage curves for sand (<0,5 mm) at different matric potentials

(1966). The implication of this is that diffusion of oxygen to the electrode is now no longer controlling the measured current. This throws doubt on the diffusion model of Fig. 1.3 and has important implications in the interpretation of measurements made with the diffusion model in mind.

In the light of this, if the platinum microelectrode method is to be used for measuring oxygen flux in soils, a thorough appraisal of the factors affecting its operation must be made. Following McIntyre's (1970) lead, therefore, electrochemical, chemical and physical factors affecting reduction of oxygen at the electrode, and operation of the method in three-phase systems will be examined.

1.3 Factors affecting oxygen flux measurement in three-phase systems

1.3.1 Electrochemistry

Electrochemical analysis is important in determining which process controls current resulting from oxygen reduction at the working electrode. It is necessary to know the nature of the reaction, its products and their subsequent behaviour, the influence of transport processes and of pH in determining electrode response. One can then deduce, using experimental evidence, likely rate-controlling processes in soils where a variety of conditions may be met. The object is to determine whether transport of oxygen, or some other process, is dominant in controlling the rate of reduction of oxygen and hence current.

a) Reaction

There is a good deal of controversy among electrochemists as to the exact reaction occurring when oxygen is reduced at the platinum microelectrode. Williams (1966) proposed two substantially different courses for the reaction. The first involves production of H_2O_2 and its subsequent reduction;

$$O_2 + 2H_2O + 2e^- \longrightarrow 2OH^- + H_2O_2$$
$$H_2O_2 + 2e^- \longrightarrow 2OH^-$$
$$O_2 + 2H_2O + 4e^- \longrightarrow 4OH^- \qquad 1.7$$

The alternative hypothesis suggests that electroreduction of oxygen proceeds at a metal electrode by the formation and subsequent decomposition of surface oxides. In this case the reaction is;

$$O_2 + 2M \longrightarrow 2MO$$
$$2MO + 2H_2O + 2e^- \longrightarrow 2MOH + 2OH^-$$
$$2MOH + 2e^- \longrightarrow 2M + 2OH^-$$
$$O_2 + 2H_2O + 4e^- \longrightarrow 4OH^- \qquad 1.8$$

Both reactions require four electrons for the reduction of a molecule of oxygen and reaction 1.8 shows formation and destruction of an oxide and hydroxide of the metal.

There is no general agreement on the course of the reaction, but the most feasible explanation, taking into account experimental evidence, is that of Rickman, Letey, Aubertin and Stolzy (1968). They concluded from their work that H_2O_2 is formed regardless of the state of oxidation of the electrode, but that its rate of catalytic decomposition depends on the presence of an 'active' oxide. They also give evidence of the formation and decomposition of oxides on the electrode. This seems to indicate that the overall reaction might be a combination of the above two reactions. Thus, whatever the actual route taken by the reaction, it appears necessary that for the reaction to proceed platinum oxides or hydroxides must be present or be formed during the reaction. These oxides may then, in turn, affect the catalytic decomposition rate of H_2O_2.

b) Reaction rate

The rate of reaction at platinum surfaces is highly dependent on the surface condition of the platinum. Four general initial surface conditions have been recognized (Black and Buchanan, 1966). These are:

1) preoxidized, anodized (or chemical treatment, e.g. HNO_3);
2) prereduced, cathodized (or chemical treatment, e.g. H_2SO_4);
3) abraded (clean);
4) aged-oxidized (any of the above surfaces allowed to stand in water or air).

Preoxidized electrodes apparently allow the greatest reaction rate (Lingane, 1961), while an aged-oxidized surface inhibits oxygen reduction (Rickman et al., 1968). In addition these authors have shown that the state of oxidation of the electrodes affects the decomposition potential of oxygen at the electrode.

In addition to the effect of surface conditions per se on reaction rate, another factor arises in unsaturated sytems. In an unsaturated medium, say a soil at 10% air porosity, solid and liquid geometry will be such that over a significant proportion of the electrode surface only very thin water films would separate the electrode from the gas phase. Consequently, oxygen concentration gradients may be high, and a significant area of the electrode is potentially able to receive oxygen at a very high rate. The current over this area will thus be controlled by the reaction rate.

McIntyre (1970) points out that if reaction rate is likely to be a current-limiting process (which is highly likely in a three-phase system), surface conditions of the electrode at time zero should be made uniform to ensure that time is not having a further effect through its control of the state of the surface. This introduces the problem of electrode standardization and how best to pretreat the electrodes to bring their surfaces to a standard condition. Techniques vary from purely physical, through chemical to electrochemical. The relative merits of the different techniques will be discussed more fully later.

1.3.2 Effect of pH

The pH of the medium surrounding the electrode is important

because it may influence electrode behaviour by changing:

1) the exact course of the reaction,
2) the decomposition potential (or half-wave potential) of oxygen,
3) the decomposition potential of H^+ ions, or
4) the effective area of the electrode by precipitation of insoluble compounds on its surface.

pH may also affect the rate of reduction by affecting H_2O_2 decomposition, H_2O_2 being more stable in acid than in alkaline solutions.

Oden (1962) has shown, from theoretical and experimental investigations, that the overall reaction already discussed, i.e.

$$O_2 + 2H_2O + 4e^- \longrightarrow 4OH^- \qquad 1.9$$

is relevant to a lower pH limit of about 3,5 to 4,0 for air-saturated solutions. Under more acid conditions than this the reaction is probably

$$O_2 + 4H^+ + 4e^- \longrightarrow 2H_2O \qquad 1.10$$

(Kolthoff and Lingane, 1952). Because soil pH is generally above 4,0 reaction 1.9 should hold for most situations.

McIntyre (1970), on the evidence of Sawyer and Interrante (1961) and Black and Buchanan (1966) regards the effect of pH on decomposition potential of oxygen to be of only minor importance. The effect of pH on decomposition potential of H^+ ions is, however, of more importance. This is especially so in anaerobic or near-anaerobic media. Current-voltage curves presented by Black and Buchanan (1966) for two-phase media show that for air-saturated soil solutions, pH has little apparent effect on decomposition potential of H^+ for values between about 3,5 and 11,0, but that below a critical pH of about 3,5 the decomposition potential of H^+ increases rather rapidly. Oden (1962) has pointed out that as oxygen concentration decreases, the critical pH for significant H^+ ion decomposition rises above 3,5. Under near-anaerobic conditions,

application of the voltages (-0,65 V, Birkle, Letey, Stolzy and Szuszkiewicz, 1964) often employed in the measurement of oxygen flux may well give rise to a current that will be wrongly interpreted as oxygen reduction. Armstrong (1967) has shown that in a two-phase system at pH 6,3 the H^+ decomposition potential changes from about -0,8 V for air-saturated to -0,5 V for near-anaerobic conditions.

Oden (1962) determined the relation between voltage at the beginning of the reaction $2H^+ + 2e^- \longrightarrow H_2$ and the pH of an oxygen-free solution. This relationship is shown in Fig. 1.6 and it can be seen that at a pH of 4,0 (a practical lower limit for most soils) the decomposition potential for H^+ ion (H^+ ion overpotential) in an oxygen-free solution is approximately -0,55 V. It would be necessary therefore to apply a potential greater than this to the platinum microelectrode to ensure that H^+ ion reduction is not taking place under anaerobic conditions. Black and West (1969) using slurries and saturated sand found that when the applied voltage was -0,4 V or more, current did not change over the pH range 5,4 to 3,2; more negative voltages gave much higher currents at pH 3,2. On the basis of this they recommended that the maximum negative potential which should be applied to a platinum microelectrode for the measurement of oxygen flux in water-saturated soils should be -0,4 V (versus saturated calomel electrode).

On this evidence it seems that at the applied voltage advocated and used by Birkle *et al.*, (1964), viz. -0,65 V (versus Ag/AgCl), H^+ ion reduction will be taking place in many poorly-aerated soils.

1.3.3 Electrode poisoning

The term 'poisoning' has been variously used in connection with platinum microelectrodes to denote a change in the surface of platinum which changes the sensitivity of the electrode to reduction of oxygen (Birkle *et al.*, 1964). It is probably better regarded as being any alteration of the electrode surface which affects its efficiency to reduce oxygen, other than by substances involved in the main process, such as platinum oxides

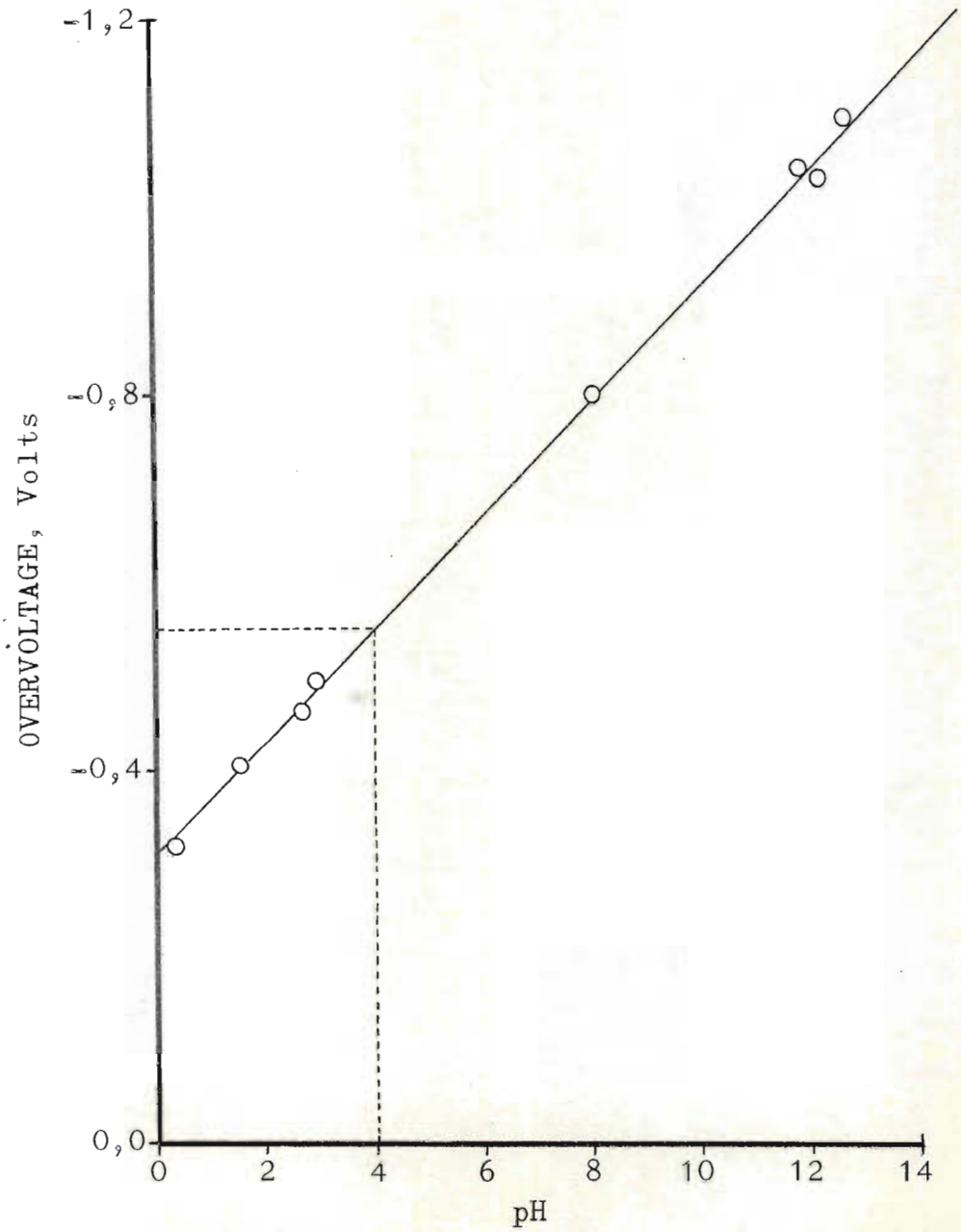


Fig. 1.6 Relation between voltage at the beginning of the reaction $2H^+ + 2e^- \rightarrow H_2$ and the pH of an oxygen-free solution (after Öden, 1962)

(McIntyre, 1970).

Oxygen flux measurements made with the electrodes left in place in the soil over long periods of time have been shown to be significantly lower than those made with freshly-inserted electrodes (Birkle et al., 1964; Rickman et al., 1968). This is thought to be due to the deposition on the electrode of salts (principally calcium carbonate) and clay particles (Rickman et al., 1968) and iron and aluminium oxides (Oden, 1962). Other substances present in soils in small or trace amounts, for example PO_4, S, Cu and As may also 'poison' the electrodes.

The simplest way of overcoming the problem of poisoning is by leaving the electrodes in the soil only as long as is required to take the oxygen flux measurement. Poisoning should not be a problem in mineral soils when the electrode is used in this way.

1.3.4 Soil resistance

In unsaturated soils, where soil resistance may be high (5 to 15 kΩ, Kristensen, 1966) there may be an appreciable potential drop (ohmic loss) between the working (platinum) electrode and the reference electrode (Fig. 1.7). A high soil resistance will have the effect of reducing the potential 'effective' at the platinum microelectrode. If V_a is the voltage applied to the electrode system, R_m is the resistance between the same electrodes, and i is the current flowing, then the effective voltage V_e is given by

$$V_e = V_a - iR_m \qquad 1.11$$

In two-phase systems soil resistance is not important, provided it is not great enough to lower V_e beyond the minimum plateau voltage (Fig. 1.2). In three-phase systems, however, where the current-voltage curves may be steep (Fig. 1.5), soil resistance assumes significant proportions. Kristensen (1966) and McIntyre (1966) have discussed this aspect and have shown that this effect alone invalidates comparison of values of

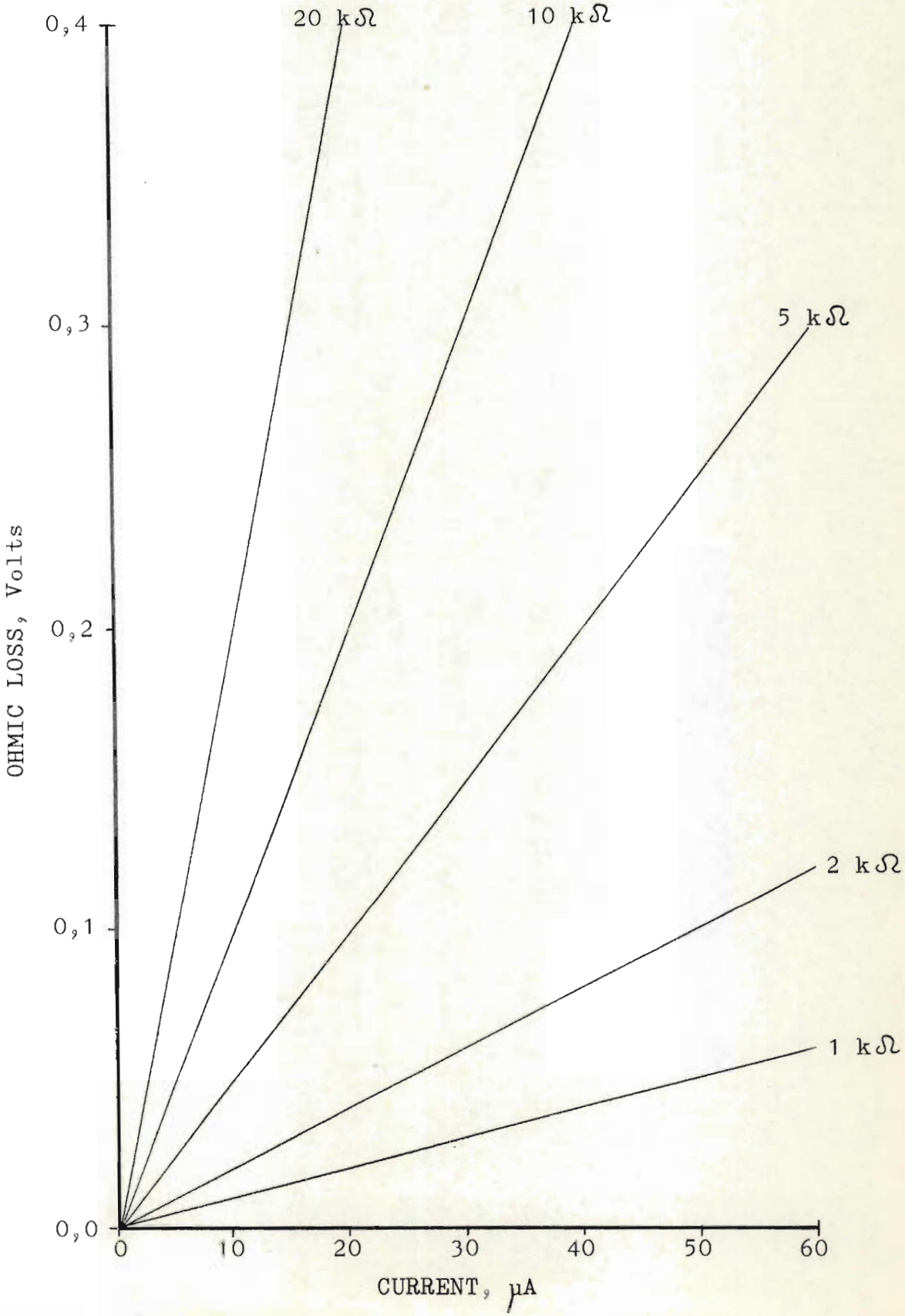


Fig. 1.7 Ohmic loss as a function of current for different resistances (after Kristensen, 1966)

oxygen flux determined in three-phase systems at constant applied voltage. In addition, despite the fact that electrical resistance has no influence on current if the applied voltage lies on a plateau in the current-voltage relation, it does affect the apparent applied voltage at which certain reactions occur. Thus, differences in decomposition and half-wave potentials, and the voltage at which pH affects the current, have no analytical significance, even in saturated media, unless ohmic loss in the medium is accounted for. Therefore, it is imperative that the resistance between the working and reference electrodes should be measured whenever oxygen flux measurements are made.

It would be expected that the resistance between two electrodes in a soil depends on the distance between the two electrodes. McIntyre (1967) has examined this. The way in which the microelectrode is used in soil gives rise to boundary conditions applicable to spherical conditions (McIntyre, 1967). For spherical conductors radii r_1 and r_2, at a distance d apart

$$R_m = \frac{1}{4\pi\sigma}\left(\frac{1}{r_1} + \frac{1}{r_2} + \frac{2}{d}\right) \qquad 1.12$$

where σ = soil conductivity. For $d \gg r_1$ or r_2, the resistance becomes independent of the distance between the electrodes, and a function of r_1, r_2 and σ only. Measurements made by McIntyre (1967), shown in Fig. 1.8, show that R_m becomes independent of d at about 100 mm. In use, therefore, the two electrodes are always separated by more than 100 mm.

1.3.5 Electrode kinetics

This section will be concerned with the 'dynamic' processes taking place at the working (platinum) electrode.

When significant current flows because of a reaction at an electrode in a medium, several nonequilibrium (rate) processes contribute to the reaction. These are:

a) the oxygen reduction rate, which is a function of voltage and state of the electrode surface;

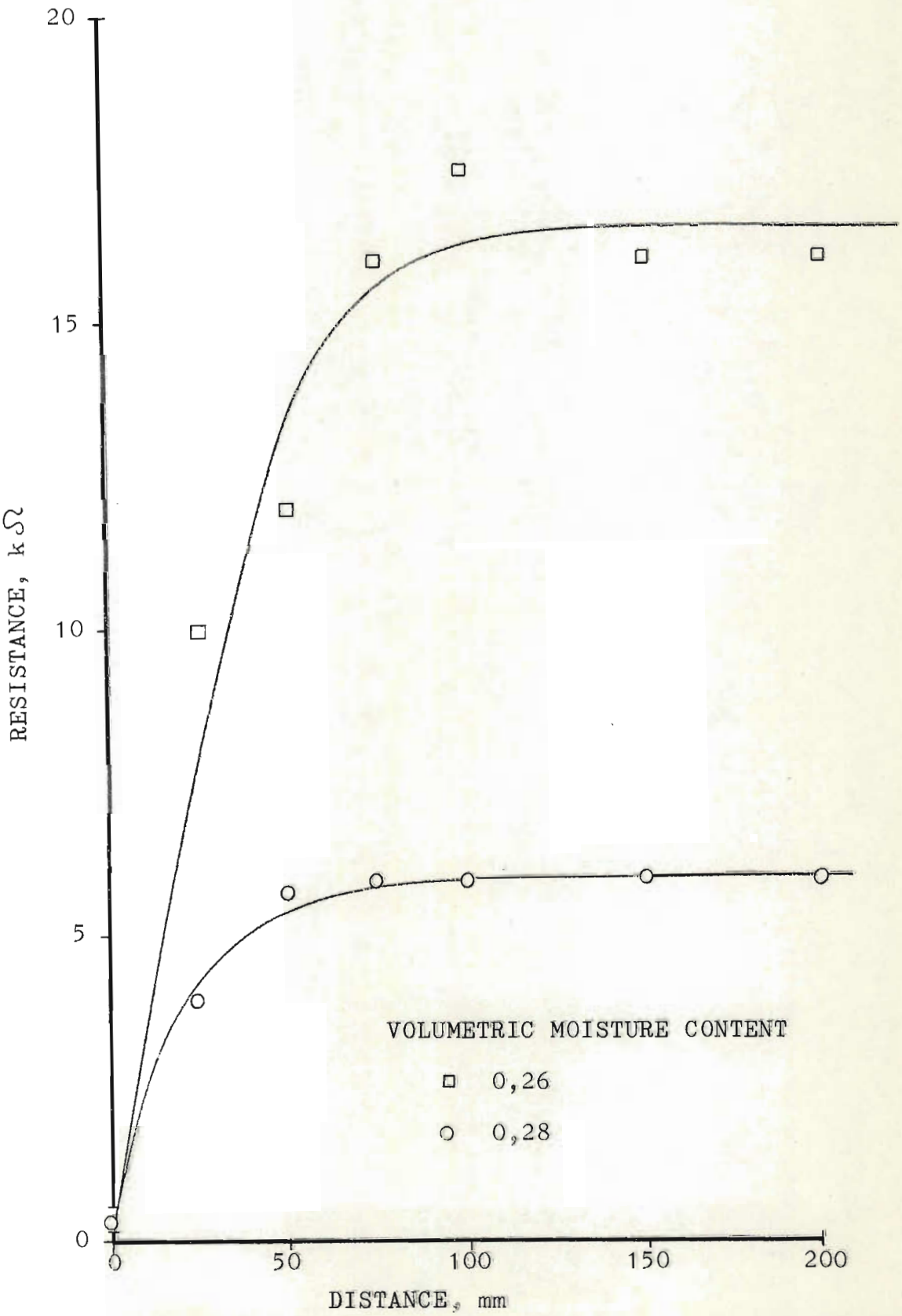


Fig. 1.8 Electrical resistance of a loam soil at two differen moisture contents as a function of the distance between the salt bridge tip and the platinum micro-electrode (after McIntyre, 1967)

b) transport of oxygen to the electrode;
c) transport of OH^- ions from the electrode, and
d) the rate of reduction of H_2O_2, if formed.

One or more of the four processes may be dominant in controlling current strength.

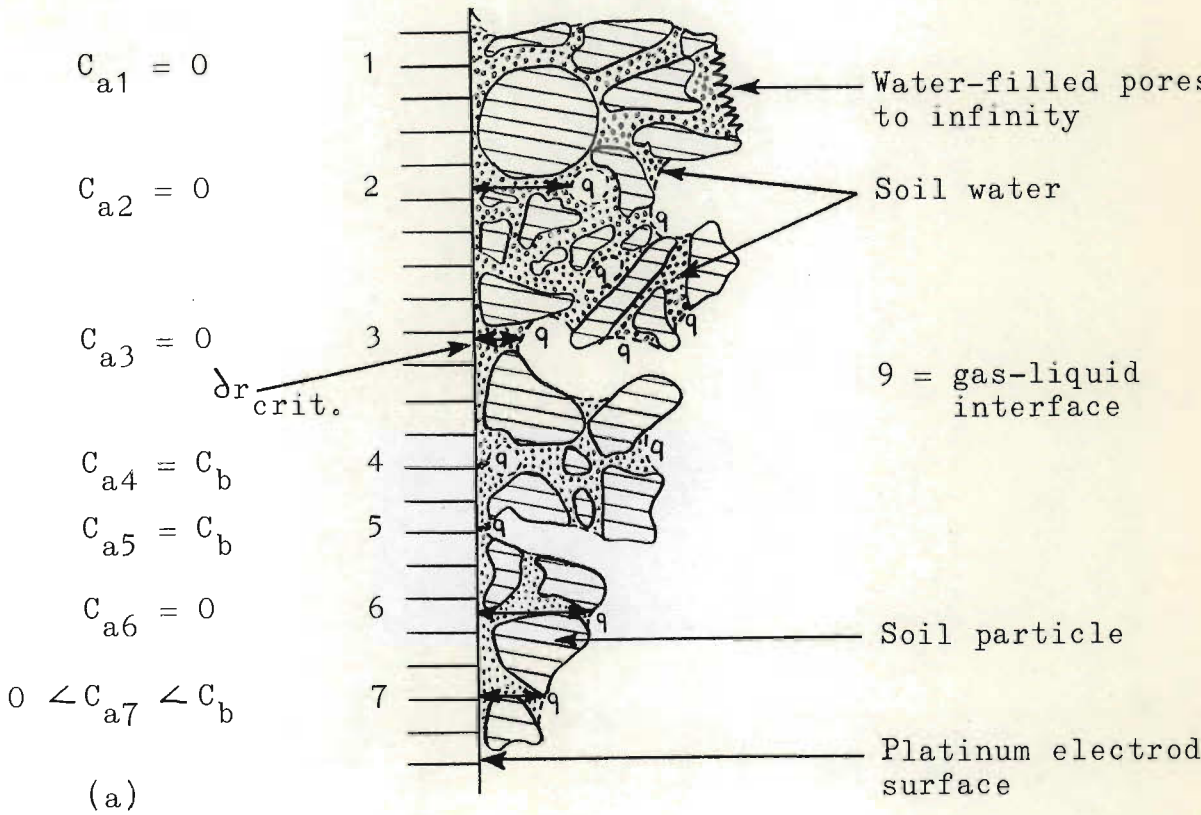
When the rate of one of the above processes becomes limiting, the electrode is said to be polarized. The types of polarization, corresponding to the rate processes described above are:

a) activation polarization due to a slow reaction rate at the electrode;
b) concentration polarization due to slow transport rates of reactants, producing concentration gradients in the medium;
c) electrolyte transport polarization, resulting from slow ion transport (by diffusion and electrical migration) from the vicinity of the electrode, and
d) reaction polarization, due to a slow secondary chemical reaction.

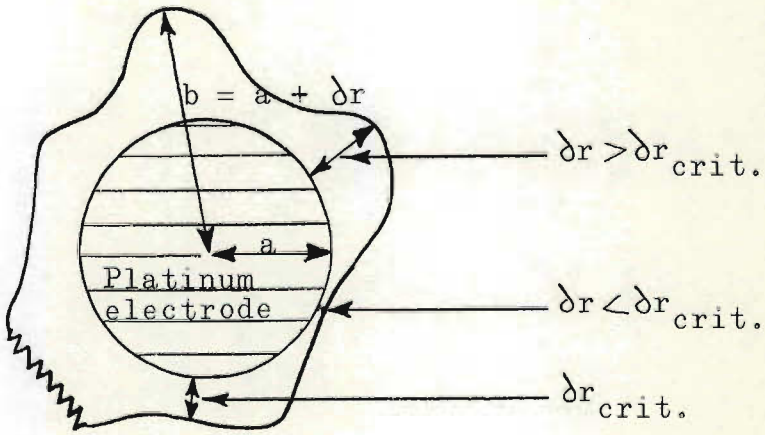
These different types of polarization tend to reduce or oppose the applied potential at the electrode, and when this occurs, the potential of the electrode deviates from its equilibrium value. In this state the electrode is said to be polarized. Activation and concentration polarization are probably the most important ones in relation to electrode response in three-phase media.

a) Activation polarization

This results from the reaction rate at the electrode being the current-limiting process, because of a slow step in the electrochemical reaction. The slow step in oxygen reduction is regarded by Evans (1968) as being that of splitting the oxygen molecule. McIntyre (1970) proposes a model to explain activation polarization. This model is shown in Fig. 1.9. Over parts of the electrode the liquid films are thin enough ($\delta < \delta r_{crit.}$) to maintain a high rate of supply of oxygen. At these points oxygen concentration is constant and in equilibrium with that in the gas phase. Activation polarization occurs as



(a)



(b)

Fig. 1.9 McIntyre's (1970) proposed model to explain micro-electrode behaviour: (a) Phase geometry at the electrode surface, (b) Schematic representation of water film separating the electrode from gas-filled pores. $C_a = O_2$ concentration at the electrode, $C_b = O_2$ concentration at the gas-liquid interface; $\delta r_{crit.}$ = minimum thickness of liquid film to maintain diffusion control of current

a result of reaction rate at the electrode being the current-limiting process.

b) Concentration polarization

When current density is high, or the reactant concentration is low, depletion of reactant oxygen may occur, causing concentration polarization. The degree of polarization increases with decrease in voltage until concentration at the electrode reaches zero, at which stage the reaction rate is completely diffusion-controlled and a limiting current is obtained. This current remains constant with further decrease in voltage until a second electrochemical reaction occurs, in this case: $2H^+ + 2e^- \rightarrow H_2$.

The case may occur when depletion of the reactant and slow reaction rate are equally effective in limitation of current. This means a combination of concentration and activation polarization at different parts of the electrode as the factors controlling current. This too is explained by the composite model of McIntyre (1970) shown in Fig. 1.9. Where $\delta r > \delta r_{crit.}$ depletion of reactant oxygen may occur and concentration polarization will take place. Where $\delta r < \delta r_{crit.}$ oxygen concentration will be high, reaction rate will be limiting and activation polarization will take place.

c) Electrolyte transport polarization

In porous media, desaturation enhances oxygen transport rates but at the same time impedes removal of OH^- ions from the electrode. This could allow a build-up of the concentration of OH^- ions near the electrode. McIntyre (1967) has discussed the build-up of OH^- ions and their subsequent migration from the electrode, in some detail.

Hydroxyl ions moving from electrodes in thin moisture films will have a velocity component parallel to the electrode surface. Will (1963) states that this would cause a potential drop along the electrode and make its effective voltage vary from point to point. If the potential drop is sufficient to

reduce the voltage over a significant area below that required for reduction of all oxygen diffusing in, the reaction would be voltage-sensitive over parts of the electrode and the current therefore dependent on applied voltage.

In addition, under unsaturated conditions OH^- ion concentration will build up in the 'diffusion layer' and the movement of these ions through this layer by electrical migration may become the dominant process. In soils with a pH of less than 6,0, neutralization of OH^- ions by H^+ ions will take place close to the electrode surface, and the electrical potential gradient will be large (McIntyre, 1970). This means that anions other than OH^- should be excluded from the 'diffusion layer', whatever the concentration of the soil electrolyte. Therefore OH^- ions will be the only carriers of current in this region, making electrolyte transport polarization likely in acid soils. If few H^+ ions are present (pH >8) the distance over which the electrical potential is active will be much greater, so that potential gradients will be small. This may allow the presence in the 'diffusion layer' of other anions as well as OH^- ions, and they will also carry the current. If salinity is high, the conditions are similar to those occurring in solutions in which an excess of indifferent electrolyte masks any influence of transport of the active ion on current. Thus electrolyte transport polarization could be expected for conditions of alkaline pH and low salinity, but not when the salt content of an alkaline medium is high; it could be expected at acid pH values irrespective of salinity.

Thus electrolyte transport may be a significant factor, and limitation of current by electrolyte transport polarization will make current continuously dependent on voltage. Current limitation by electrolyte transport polarization would be most likely to occur in relatively dry soils, in acid soils, and in soils with a low salt content.

d) Reaction polarization

This occurs when a chemical reaction precedes or succeeds the electrochemical reaction, and its rate becomes a current-

limiting factor. Thus, in the reduction of oxygen, H_2O_2 may be produced. Its catalytic decomposition is dependent upon the surface oxide condition on the electrode, and reaction polarization may occur. Hoare (1968) states, however, that decomposition rate of H_2O_2 is only likely to be limiting at high current densities.

1.4 Conclusions

An in-depth review of the platinum microelectrode technique for measuring oxygen flux has been made. Special attention has been paid to the problems not encountered in two-phase media, but which arise in three-phase media because of desaturation (cf. Fig. 1.5). On the results shown, the diffusion models of Kristensen and Lemon (1964) and Letey and Stolzy (1967) cannot be applied to results obtained in three-phase systems. A thorough appraisal of the electrochemical processes occurring at the platinum surface has been made. McIntyre's (1970) proposed model to explain microelectrode behaviour in three-phase systems is presented.

A point arising out of McIntyre's (1970) model for three-phase systems is that reduction current readings obtained are not due exclusively to oxygen flux in the soil to the electrode. Thus it is theoretically incorrect to state that oxygen flux has been measured in a soil, particularly when the soil is unsaturated. A better term would be 'oxygen flux index' (OFI). Oxygen flus index therefore gives a measure of the ability of the soil system to supply oxygen.

In summary, and before going on to discuss techniques for measuring oxygen flux index in the light of the foregoing discussion, it is pertinent to mention some of the concluding remarks made by McIntyre (1970) in his review article. These are:

1) The diffusion model probably applies only to saturated porous media. The type of behaviour of the electrode under these conditions, in which oxygen diffusion rate has an overwhelming

influence on current, cannot be extrapolated to three-phase media.

2) The composite model - activation and concentration polarization - applies to unsaturated porous media, and probably to media that are saturated but in which the water is under tension.

3) Most results obtained so far with unsaturated soils are not comparable within and between soils because soil resistance has not been measured. Comparison of results is valid only at constant effective voltage.

4) If the composite model applies, comparison of results is further invalidated, for the current will depend on the relative areas of the electrode subjected to activation and concentration polarization. These areas will vary with the structure and moisture content of the soil.

5) pH assumes more importance than previously recognized. In acid soils the possibility of reduction of H^+ ions at the often-used voltage -0,65 V is real; a better voltage would be -0,40 to -0,45 V.

CHAPTER 2

OXYGEN FLUX MEASUREMENT: EQUIPMENT DESIGN AND OPERATION

2.1 Introduction

The plateau present in current-voltage curves obtained in two-phase media disappears at an early stage of desaturation (Fig. 1.5). This produces the situation where current is continuously dependent upon voltage, and in certain circumstances current-voltage curves may be quite steep. This means that:

1) the potential applied to the electrode must be carefully controlled, and
2) the potential effective at the electrode must be known precisely.

The latter condition can be satisfied by measuring the resistance of the system, between the platinum microelectrode and the reference electrode, and correcting for ohmic loss using the relation

$$V_e = V_a - iR_m \qquad 2.1$$

where V_e = the voltage effective at the platinum microelectrode; V_a = the voltage applied to the electrode system; i = the current flowing, and R_m = the resistance between the electrodes.

Careful control of applied potential is perhaps not as simply achieved. Most workers use instruments based on the design of Letey and Stolzy (1964). In this type of instrument current is applied to several (usually 10) electrodes in parallel, and current measurements are made by successive switching of each electrode circuit through a microammeter. McIntyre (1967) points out that, unless very special conditions are met, as the electrodes are switched through the microammeter, the voltages applied to the individual electrodes will change. These changes may be small, but in the case of steep current-voltage curves will be significant.

Therefore, an instrument is required which will fulfil two

main conditions. These are:

1) there must be no change in potential applied to any electrode while reduction current is being measured, and
2) the instrument must contain facilities for measuring soil resistance, so that the effective voltage at the electrode can be calculated.

When an electric current flows through a resistor, there is a potential drop between the ends of the resistor. If a sensitive voltmeter is connected across the resistor, and the resistance of the resistor is known, the current flowing in the circuit can be calculated ($i = V/R$). Utilizing this principle then, an instrument has been designed to measure oxygen reduction current accurately in two-phase and three-phase media. The instrument includes facilities for measuring soil resistance, and, for reasons to be discussed later, electrode potential can also be measured.

2.2 Circuit design and construction

The circuit diagram of the new instrument is shown in Fig. 2.1. One kilohm precision resistors are incorporated into each electrode circuit. Current flow in each resistor is obtained by measuring the potential drop across the resistor with a high internal resistance microvoltmeter. This draws negligible current and so has little effect on the voltage at the electrode during measurement. Soil resistance is measured with an AC conductivity bridge reading directly in ohms.

Two rechargeable nickel-cadmium batteries (B_1) supply current to the potential divider circuit. The potential to be applied is set using the 'coarse' ($R_1 = 100\,\Omega$) and 'fine' ($R_2 = 500\,\Omega$) wire-wound potentiometers. The values of R_3 ($120\,\Omega$) and R_4 ($470\,\Omega$) were chosen to give a range of 0 - 1 V on the coarse control, and a fine adjustment of approximately 5% of the value set with the coarse control.

The adjustable post of potentiometer R_1 is connected to

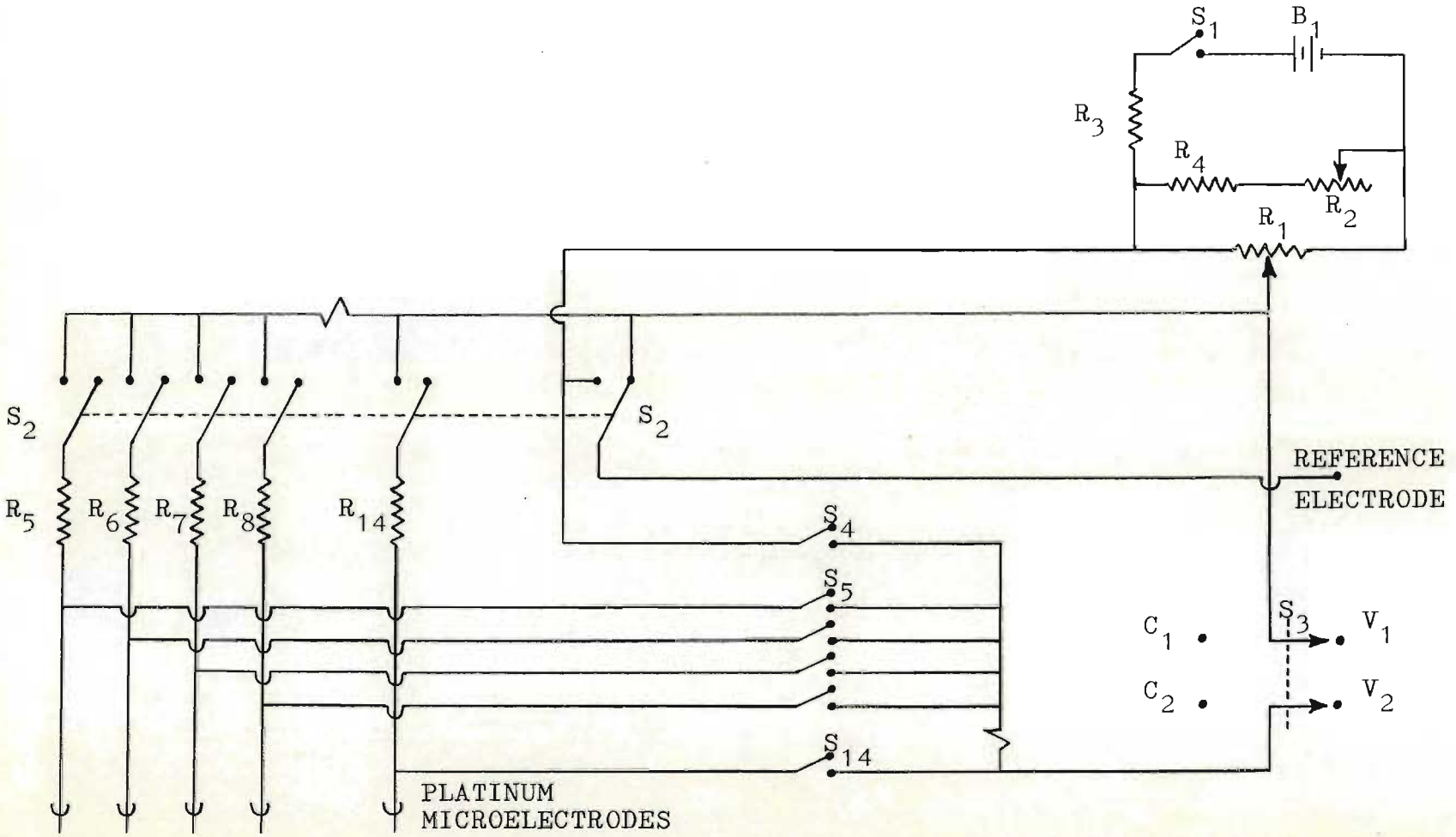


Fig. 2.1 Circuit diagram of oxygen flux meter

one central terminal of S_3 and to the common source on switch S_2, a 12-pole, 2-way rotary wafer switch. In the 'closed' position this supplies current to the 10 electrode circuits through the 1 kΩ resistors (R_5 - R_{14}). A DC microvoltmeter (Philips PM 2435) is connected across V_1V_2 of DPDT switch S_3, and an AC conductivity bridge (Philips PM 9500) is connected across C_1C_2 of S_3. Switches S_4 and S_5 - S_{14} are single-pole push button, biased off switches.

Platinum microelectrodes used in this investigation were constructed according to the design of Letey and Stolzy (1964), and a saturated Ag/AgCl reference electrode was used throughout.

2.3 Operation of the oxygen flux meter

2.3.1 Measurement of oxygen flux

For measurement of oxygen flux index a predetermined potential is set, and then applied to the electrodes. After a set time current flowing in each electrode circuit is measured. The potential to be applied to the electrodes is first set with switch S_2 'open', and switch S_1 closed, i.e. current being supplied to the external circuit, but with the electrodes switched out. With the DC microvoltmeter connected across V_1V_2, switch S_4 is depressed. The potential being applied to the external circuit is registered by the microvoltmeter. This potential can be changed using the coarse and fine controls, R_1 and R_2, respectively.

With switches S_1 and S_2 open, the electrodes (platinum and reference) are positioned in the medium in which oxygen flux is to be measured. Switches S_1 and S_2 are then closed. This supplies current to the electrode system. The applied potential can then be checked again by depressing switch S_4, noting the reading on the microvoltmeter and adjusting, if necessary, with R_2. After the set time following application of the potential (four minutes) current flowing in each electrode circuit is measured by depressing in turn, switches S_5 - S_{14} (or fewer, if fewer electrodes are in use). The potential

drop across each 1 kΩ resistor is then registered on the microvoltmeter. Potential difference readings on the microvoltmeter in millivolts convert directly to current in microamps (1 mV potential drop across 1 kΩ gives a current of 1 μA).

When measuring oxygen reduction current the microvoltmeter is set to its 'mV' range. On this range the internal resistance of the microvoltmeter is 1 MΩ, and less than 0,1% of the current flowing through the standard resistor flows through the meter. Thus the effect on the electrodes of the measuring system is negligible, and there is no change in potential at the electrodes during measurement. This satisfies one of the requirements of an instrument used under conditions where current-voltage curves may be steep.

2.3.2 Measurement of soil resistance

Soil resistance is measured with the electrodes still in place, immediately after oxygen reduction current has been measured. Switch S_1 is switched off and S_2 is switched to its 'open' position. S_3 is switched across to connect in the AC conductivity bridge. The electrode-soil system is fed with a 1 kHz alternating current (this prevents polarization from occurring at the electrodes). Switches S_5 to S_{14} are then depressed in turn, the bridge balanced, and the soil resistance, in ohms, recorded. The value obtained is used to calculate the effective voltage at the electrode.

2.3.3 Measurement of electrode potential

The need to measure electrode potential will be discussed in more detail in the next section, but basically, electrode potential gives a measure of the surface oxide condition of the electrode and its behaviour during oxygen reduction (Sandler and Pantier, 1965).

With the platinum and reference electrodes immersed in a standard clay suspension (van Doren and Erickson, 1966), S_2 in the open position, and S_3 set to connect in the microvoltmeter, switches S_5 - S_{14} are depressed in turn. Electrode potential

are registered on the meter. For electrode potential readings the microvoltmeter is set to its 'V' range on which it has an internal resistance of 100 MΩ. On this range the current drawn by the meter is low (<3 nA). This permits the electrode to express its potential without discharge (Bohn, 1971).

2.4 Electrode behaviour

Black and Buchanan (1966) recognize four general initial surface oxide conditions. These are:

1) preoxidized, anodized (or chemical treatment, e.g. HNO_3);
2) prereduced, cathodized (or chemical treatment, e.g. H_2SO_4);
3) abraded (clean), and
4) aged-oxidized (any of the above three surfaces allowed to stand in water or air).

These different surface treatments affect the amount and type of oxide existing on the electrode surface. Rickman *et al.* (1968) discuss in some detail the effect of these oxides on the reduction of oxygen at the platinum microelectrode. Platinum oxides affect the behaviour of electrodes to oxygen reduction in two main ways. Firstly, the oxygen atoms bonded to the platinum surface are an integral part of the oxygen reduction mechanism at the electrode surface. Secondly, the amount and type of oxide on the electrode determine the potential at which oxygen reacts at the surface. Four different oxide forms appear to exist on platinum electrodes (Rickman *et al.*, 1968). Two of these forms are platinum oxide and platinum dioxide. A third form has more oxygen per unit atom than the dioxide, and the last is an irreversible oxide of unspecified composition, formed by ageing of the electrode surface. This latter oxide form has been shown by Sandler and Pantier (1965) to inhibit oxygen reduction. The rate of catalytic decomposition of H_2O_2 (generally regarded to be a primary product of oxygen reduction) depends upon the presence of an 'active' oxide.

Rickman *et al.* (1968) have demonstrated, using constant

current analysis, the formation and removal of oxides on platinum microelectrodes. They also found that oxygen begins to react at the surface of a platinum electrode at different potentials, depending upon the degree of oxidation of the electrode surface. Thus, they showed that oxygen began to react on an oxidized surface at a potential 0,2 to 0,3 V higher than on a reduced surface.

Sandler and Pantier (1965) suggest that changes in electrode potential cause a change in the amount of surface oxide on the electrode. The corollary to this is that the catalytic properties of an electrode should be a function of its potential. Thus, if electrode potential is measured prior to the electrode being used to measure oxygen flux, this should provide an index of the capacity of the electrode surface to support oxygen reduction (Rickman et al., 1968).

During measurement of oxygen flux index a cathodic (reducing) current is applied to the platinum microelectrode, and this shifts its potential towards that of a reduced electrode. With successive uses the potential at which oxygen begins to react on the platinum becomes lower and lower. The selection of a constant potential to apply to an electrode presumes that the shift in potential will not be great enough to move the selected potential from the diffusion plateau of the current-voltage curve. In unsaturated soils, however, where diffusion plateaus are non-existent, the shift of a current-voltage curve toward a more negative voltage along the voltage axis may cause successive measurements from an electrode at a specific potential in a given medium to be progressively smaller.

This prompts consideration of two factors:

1) the effect of the surface oxide condition, as measured by electrode potential, on oxygen reduction current measured in a standard medium; and
2) the need for some form of standardization process to bring the electrode surface to a similar condition each time before use.

2.4.1 Electrode potential-current relations

a) Experimental procedure

All measurements of electrode potential and oxygen reduction current were made in the standard medium used by van Doren and Erickson (1966). This was a 3% suspension of bentonite in 0,1N KCl. The thixotropic nature of the suspension resulted in a reproducible diffusion medium with few, if any, eddy currents to disturb the steady-state oxygen concentration gradient created by the reaction at the platinum surface. Before use the clay was thoroughly dispersed in a blender.

Successive readings of electrode potential and oxygen reduction current were made in each of two series of readings with four electrodes. Prior to the first measurement in each series, the electrodes were abraded in wet fine sand. This gave a high initial electrode potential which decreased during subsequent measurements. The electrodes remained submerged in the clay suspension throughout each series of determinations. The clay suspension was stirred with a paddle stirrer between each measurement. Applied potential was -0,40 V versus Ag/AgCl, and oxygen reduction current readings were taken four minutes after current was applied. All readings were made at 22 $\pm$ 1C.

Two series of readings were made. In the first series the electrodes were exposed to the air for two hours after abrasion and before measurement of oxygen reduction current. In the second series the electrodes were abraded in wet sand and transferred immediately to the clay suspension.

b) Results and discussion

Electrode potential and oxygen reduction current readings for the two series of measurements are shown in Fig. 2.2. (Individual data points and regression analysis of variance are presented in appendix 2.1 and 2.2 respectively.) Within each series the data show a very highly significant linear relationship between electrode potential and oxygen reduction

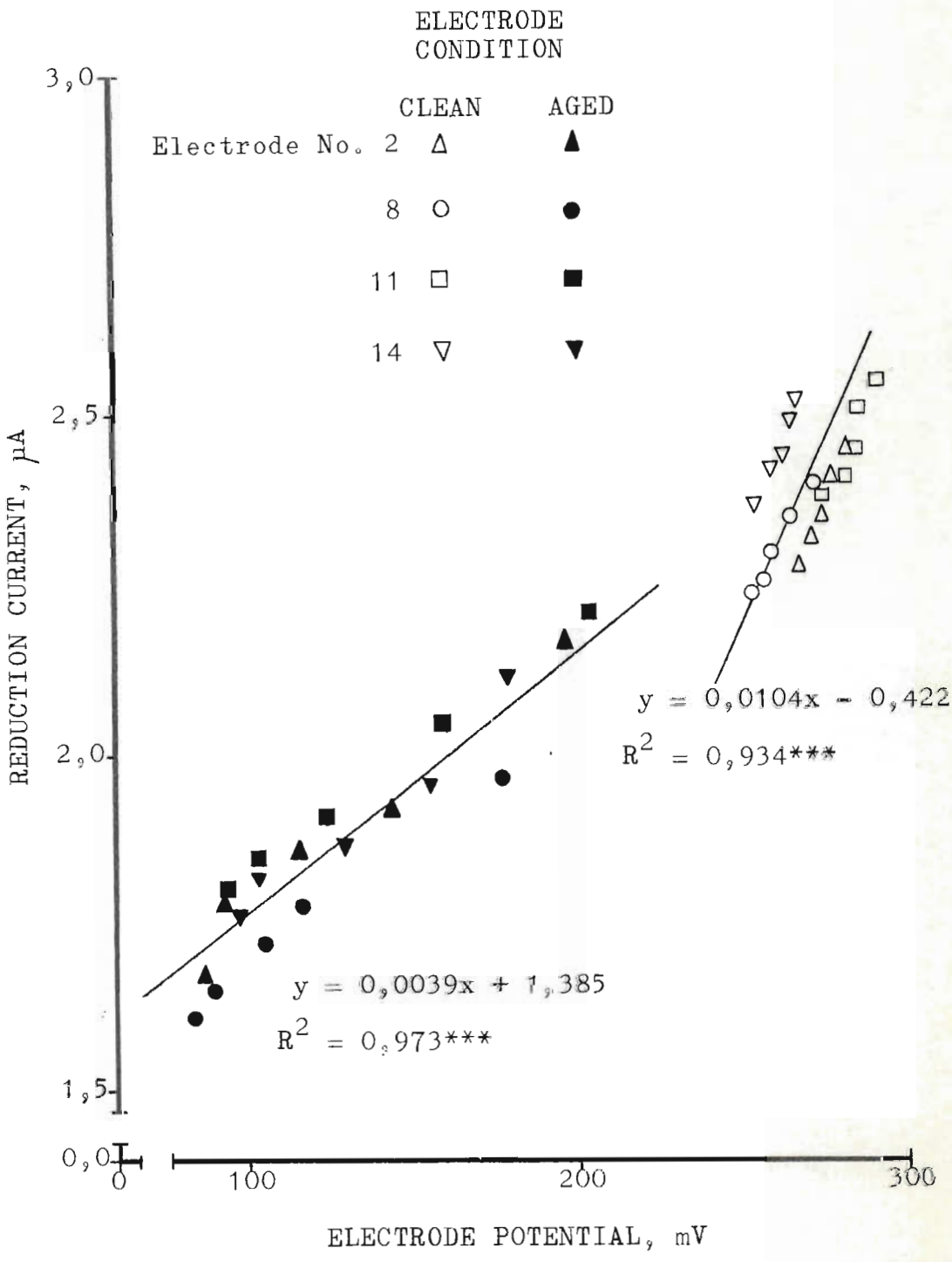


Fig. 2.2 Successive readings of electrode potential and oxygen reduction current with four electrodes in two different conditions

current. There is also a very highly significant difference in the regression slopes for the two surface conditions.

Considering first the relationship between electrode potential and oxygen reduction current, Rickman et al. (1968) predicted this relationship on theoretical grounds, but were unable to prove it experimentally. This they attributed to the fact that their measurements were made in a standard medium which restricted current density on the electrodes to a very low value ($\lesssim 4$ mA m^{-2}). They felt that at higher current densities (> 40 mA m^{-2}) the state of oxidation of the platinum surface would influence measured current. In the experiment described in this investigation, current densities were low ($\lesssim 4$ mA m^{-2}), but nevertheless a highly significant relationship was found between electrode potential and oxygen reduction current. This is probably due to the fact that the electrodes remained submerged in the clay suspension between readings.

In this investigation both initial surface oxide conditions (clean and aged) have shown progressive decreases in both potential and oxygen reduction current during use of the electrodes to measure oxygen flux. The reason for this is that with successive use the potential at which oxygen begins to react on platinum becomes lower and lower (Rickman et al., 1968).

The second interesting observation from the results shown in Fig. 2.2 is the difference in slope and position of the regression relations obtained for the clean and aged electrode surfaces. The 'clean' electrodes were submerged in the clay suspension immediately after abrasion, while the 'aged' electrodes were exposed to the atmosphere for two hours after abrasion. During this exposure the oxide shown by Sandler and Pantier (1965) to inhibit oxygen reduction was probably formed, measured current therefore being lower due to the presence of this oxide.

The lower slope of the regression relation between electrode potential and oxygen reduction current for the aged electrodes is a little more difficult to explain. Two factors, viz. inhibition of oxygen reduction by the irreversible oxide and

the potential at which oxygen begins to react are interacting. In addition, the irreversible oxide affects the surface oxide condition and thus the potential expressed by the electrode in the standard medium. These factors combine to give a lower slope to the regression relation.

The results of this experiment show the necessity for some form of electrode pretreatment to bring the electrode to a standard surface condition (as measured by its potential) if reproducible results are to be obtained. This point is also made by McIntyre (1970).

2.4.2 Electrode pretreatment

Many different pretreatment techniques have been developed and used. These range from electrochemical through chemical to physical methods. Black and Buchanan (1966) suggested an electrochemical technique in which the electrodes were anodized in an acid medium at +1,5 V for several minutes, then cathodized at -1,5 V in saturated KCl to which phenolphthalein had been added. The electrodes were then equilibrated overnight in the latter solution before use. Hoare (1965) used a chemical technique for pretreatment. He soaked the electrodes in concentrated nitric acid for 72 hours. Both these techniques, although they undoubtedly produce standard surface conditions, require a fairly long period of time before the pretreatment process is complete. The main requirements of an electrode standardization method are that it should be simple, reproducible and quick. This precludes the electrochemical and chemical techniques described above. A simple technique, that of abrading the electrodes in sand has been used with apparent success by McIntyre (1970). The effectiveness of electrode abrasion in sand as a standardization technique was then tested in the following experiment.

a) Experimental procedure

A series of 12 measurements each with five electrodes was made over a period of two days. Before each measurement the electrodes were abraded in wet sand ($\angle$ 0,5 mm), and then trans-

ferred immediately to the standard clay suspension described previously. Electrode potentials and subsequent oxygen reduction currents four minutes after current application were measured. Applied voltage was -0,40 V. Six sets of measurements were made on each day, with the total time between successive measurements being approximately 15 minutes. The suspension was stirred with a paddle stirrer between successive measurements.

b) Results and discussion

The mean potential and current readings for the five electrodes for each set of measurements are shown in Table 2.1.

TABLE 2.1

Mean electrode potential and oxygen reduction current readings for five electrodes measured 12 times over two days

Day 1		Day 2	
Initial potential mV	Reduction current µA	Initial potential mV	Reduction current µA
278+	2,53+	283+	2,65+
292	2,60	291	2,62
295	2,61	290	2,61
294	2,60	290	2,61
296	2,61	288	2,60
302	2,60	285	2,59

+Readings rejected in subsequent analysis (see text)

The readings obtained in the first set of measurements on each day were erratic and not consistent with the readings obtained subsequently (see Appendix 2.3 for individual electrode readings). This was probably due to the presence of the 'irreversible oxide' on the platinum surface which formed on ageing. This was not completely removed before the first set of readings on each day. After one cycle of abrasion and reduction the electrode potential and current readings were consistent. This procedure was adhered to in subsequent

measurements i.e. prior to being used electrodes were taken through one or sometimes two cycles of abrasion in sand and reduction in the standard clay suspension.

Statistical analysis was performed on the data, rejecting the first set of readings on each day. The coefficient of variation of measured current was 0,8%. The difference in current readings of the five electrodes arose because of differences in surface area of the electrodes. The results show that sand abrasion is a suitable technique for pretreating electrodes. The method is quick, simple and produces reproducibl surface conditions on the electrodes.

Subsequent experience with electrodes used in soils led to the adoption of a standard potential of +270 $\pm$ 10 mV (versus Ag/AgCl). Electrodes were only used when their potential was within this range. This condition was usually easily attained. Electrode potential higher than +280 mV indicated over-abrasion. Reduction and gentle reabrasion usually brought the potential back into the required range. Low potentials and difficulty in getting the electrode potential up to +270 mV indicated a breakdown in the epoxy resin at the tip of the electrode, and subsequent leakage. Electrodes in this condition were rejected.

2.4.3 Standard measurement method

Before use electrodes were abraded by twisting in wet sand. If the electrodes had been unused for a while they were put through a cycle of reduction and reabrasion. Electrode potential was then measured in the standard clay suspension (3% bentonite in 0,1N KCl). Electrodes were only used if their potential was within the range +270 $\pm$ 10 mV.

An <u>effective</u> potential of -0,40 V was used. In conditions of low soil resistance (usually associated with high soil moisture and low oxygen flux index) this meant that the applied potential was also -0,40 V. Where soil resistance or measured current was high, and ohmic loss became appreciable, an applied potential was set slightly lower than -0,40 V, so that the effective potential would be -0,40 V. If the approximate soil

resistance and/or current was not known prior to measurement, two sets of measurements either side of the effective potential were made. The oxygen reduction current at an effective potential of -0,40 V was then obtained by interpolation. Soil resistance was measured with the electrodes left in position after reduction current measurement. Applied voltage was always corrected for ohmic loss, and current readings were taken four minutes after current application. The distance between the reference electrode and platinum microelectrode was always >100 mm.

2.5 Measurement of oxygen flux index in soil

The instrument and measurement technique described previously were then tested in samples from two horizons in each of two soils

2.5.1 Experimental procedure

A Marandellas G1 soil at Grasslands Research Station, Marandellas, Rhodesia, was sampled at 0 - 200 mm and 200 - 400 mm and a Shortlands soil at Broadacres, Cedara, Natal was sampled at 0 - 300 mm (Orthic A) and 450 - 600 mm (Red structured B). The soils were air-dried and passed through a 2 mm round hole sieve. Nine hundred grams of each of the two surface samples, and eight hundred grams of each of the two subsurface samples were poured through a wide-mouthed funnel into each of five rigid PVC cylinders. The cylinders (100 mm high and 100 mm diameter) were closed at one end by a circle of cloth held in place by a rubber band. The soils which were gently tamped in the cylinders occupied a depth of approximately 80 mm.

The five cylinders of each sample were then placed on a tension tray and soaked overnight in 0,1N KCl. (In a preliminary run with the cores soaked in distilled water, soil resistance was high and very variable. Soaking in 0,1N KCl reduced the resistance, and variability was considerably reduced.)

The cylinders were drained to successively decreasing matric potentials (measured with respect to the bottom of the cylinder)

on the tension tray, and in one case on a ceramic plate in a pressure plate extractor. Oxygen flux index was measured in each of four of the cylinders. The fifth cylinder, placed equidistant from the other four on the tension tray was used for the porous tip of the reference electrode. Distance between the platinum and reference electrodes was approximately 150 mm. Oxygen flux index measurements were the mean of four readings, one electrode per cylinder in the Marandellas soils, and the mean of eight readings, two electrodes per cylinder in the Shortlands soils, at each matric potential. Soil resistance was measured in each case. An effective potential of -0,4 V was applied which was accomplished by applying a slightly lower potential where ohmic loss was appreciable. Correction for ohmic loss brought the effective potential up to -0,4 V. Current readings were made four minutes after the potential had been applied.

After equilibration and measurement of oxygen reduction current at a particular matric potential, the cores were weighed. This enabled moisture contents, and by difference, air space at each matric potential to be calculated.

2.5.2 Results and discussion

Oxygen flux index measurements in the two soils at different matric potentials, with their corresponding air space, are shown in Table 2.2. Oxygen flux index is relatively high at saturation decreases to a minimum and then increases.

The amount of oxygen (and thus oxygen flux index) in a soil microsite at any given time is primarily a function of the biochemical oxygen demands of soil organisms and plant roots, and of the rate of oxygen movement into the soil atmosphere and through the water barriers surrounding the respiring organisms (Clark and Kemper, 1967).

When a soil is saturated, air becomes entrapped within the soil fabric, and oxygen, being fairly soluble (3,16 cm^3/ 100 cm^3 at 25C, Weast, 1968) dissolves in the soil solution.

TABLE 2.2

Air space and oxygen flux index in samples of Marandellas G1 and Shortlands soils at different matric potentials

Marandellas G1

Matric potential mbar	Surface (0-200 mm)		Subsurface (200-400 mm)	
	Air space %	Oxygen flux index $\mu g\ m^{-2}\ s^{-1}$	Air space %	Oxygen flux index $\mu g\ m^{-2}\ s^{-1}$
Sat.	0	6,8	0	5,7
0	3,5	4,5	4,3	2,4
-20	7,9	12,2	14,5	34,1
-30	12,4	33,2	19,0	57,6
-40	17,3	90,8	22,5	95,2
-60	22,9	153,4	26,3	109,1

Shortlands

Matric potential mbar	Surface (0-300 mm)		Subsurface (450-600 mm)	
	Air space %	Oxygen flux index $\mu g\ m^{-2}\ s^{-1}$	Air space %	Oxygen flux index $\mu g\ m^{-2}\ s^{-1}$
Sat.	0	3,8	0	26,2
0	0,9	1,6	2,1	12,7
-20	3,3	0,6	4,6	2,9
-30	ND	ND	6,6	13,8
-40	5,6	8,2	9,3	19,8
-60	8,6	18,4	12,5	23,4
-80	11,6	25,5	14,7	32,4
-100	13,2	29,0	16,2	39,4
-150	19,9	41,3	ND	ND

ND = Not determined

Measurement of oxygen flux index soon after saturation would give a high value, because the system had not yet attained equilibrium. This is shown by the results obtained in this

experiment, where oxygen flux indices at saturation were high and variable. Between saturation and about 3% air space oxygen flux indices decreased. This was probably a time effect, microbes utilizing oxygen as desaturation proceeded. At about 3% air space oxygen flux indices were at a minimum, the oxygen supplying power of the soil being very low, because of the thick water films through which oxygen has to move. (Oxygen diffusion is 10^4 times slower through water than through air.) On further desaturation oxygen diffusion within the soil improved, and oxygen flux indices increased concomitantly.

Between 3 and 15% air space there appeared to be a linear relationship between air space and oxygen flux index, whilst above 15% air space oxygen flux indices increased sharply. A linear regression analysis was therefore performed on the air space-oxygen flux index data in the range 3 - 15% air space. The overall (linear) and between soils regressions were tested. The regression analysis of variance table is presented in appendix 2.4, with the individual data points and calculated regression line being shown in Fig. 2.3. The overall regression was very highly significant, and the between soils regression was not significant. This latter point is important because the particle size distribution of the four soils studied was quite different, as is shown in Table 2.3.

TABLE 2.3

Particle size distribution of Marandellas G1 and Shortlands soils

	Marandellas		Shortlands	
	0-200 mm	200-400 mm	0-300 mm	450-600 mm
Clay %	14,4	26,2	32,1	40,5
Silt %	3,8	4,0	15,2	10,7
Sand %	81,8	69,8	52,7	48,8
Text. class	SaLm	SaClLm	SaClLm	SaCl

In the light of this very close correlation between air space and oxygen flux index, it was decided that, rather than use the latter as an index of soil aeration in cores taken from

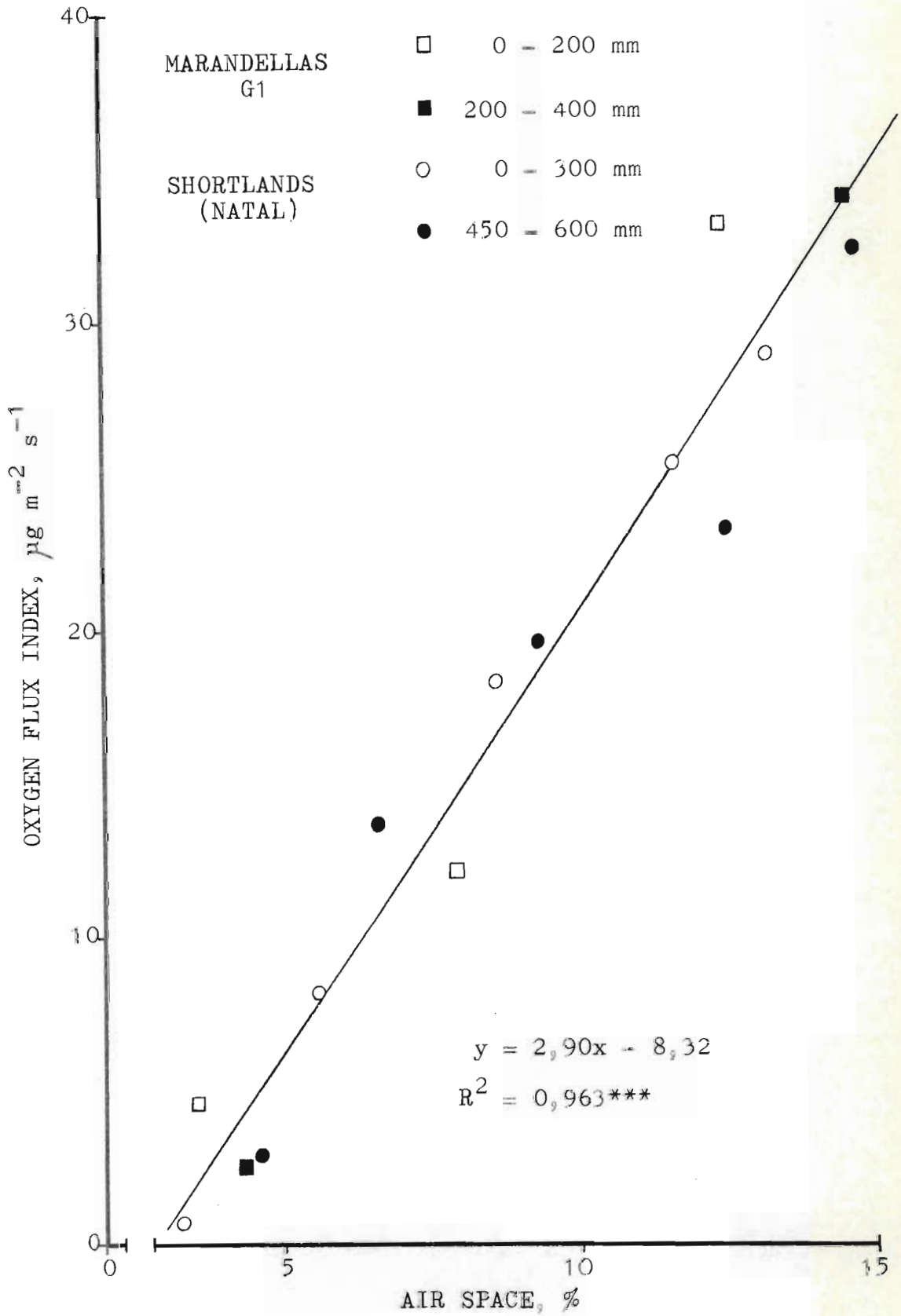


Fig. 2.3 Air space-oxygen flux index relation for two soils

the tillage trials, air space would be measured in these cores at high matric potentials, and that air space *per se* would be used to give an indication of the aeration status of the soils. Ten per cent air space, corresponding in this investigation to an oxygen flux index of approximately 20 $\mu g\ m^{-2}\ s^{-1}$, is generally regarded as being the lower limit for root growth (Baver, Gardner and Gardner, 1972). This air space limit will be used as an index of limiting soil aeration in cores taken from the tillage trials.

In order to establish what factor or factors are restricting rooting in the tillage trials studied in this investigation, undisturbed cores taken from the trials will be subjected to extensive physical measurements, viz. particle size distribution analysis, bulk density, soil strength, air space and available moisture. Chapter 3 will describe field and laboratory penetrometers which are used for measuring soil strength. This latter parameter is generally regarded as being one of the most useful indices for relating to root growth (Taylor and Gardner, 1963; Taylor and Burnett, 1964).

2.6 Summary

A new instrument for measuring oxygen flux index in saturated and unsaturated systems has been described. The main advantage of this instrument over others described in the literature is that there is careful control over potential applied to the electrode. The instrument also incorporates facilities for measuring soil resistance and electrode potential. The reasons for these requirements are discussed.

The effects of different surface conditions at the platinum microelectrode have been studied and the reasons for the resultant electrode behaviour discussed. The need for electrode pretreatment to produce standard electrode surface conditions has been established, and a simple technique for electrode standardization is described. A standard measurement technique is described, and this enables oxygen flux index to be measured with confidence in both saturated, and more important, unsaturated soils.

Measurements in four soils over a range of moisture potentials have shown a very highly significant relationship between oxygen flux index and air space in the range 3 - 15% air space. There was no significant difference in the regression relationship between the soils.

CHAPTER 3

FIELD AND LABORATORY MEASUREMENT OF SOIL STRENGTH

3.1 Introduction

The resistance of a soil to the penetration of a probing instrument is an integrated index of soil bulk density, moisture content, texture, structure and type of clay mineral. Thus it is an index of soil strength under the conditions of measurement (Baver et al., 1972). Types of penetrometer used to measure soil strength fall into two main categories, the impact and continuous stress or recording types (Vomocil, 1957). In the former, a falling mass forces the penetrometer tip into the soil, the number of blows required to force the tip a specified depth into the soil being the index of soil strength. In the latter, the penetrometer tip is forced at a constant rate into the soil and soil strength is then measured as the maximum resistance registered in forcing the tip into the soil a specified distance. Alternatively, soil strength can be measured at specified depth increments to give a soil strength/depth profile within the soil under study.

Penetrometers have been criticized on the basis of variability of the results, the empiricism of the technique and the difficulty in interpreting results (Bodman, 1949). Nevertheless, the penetrometer can be a useful tool to obtain information on soil strength and soil compaction, provided the composite nature of the effects it measures are borne in mind (Baver et al., 1972).

Field and laboratory penetrometers, designed to measure soil strength under field and closely-controlled laboratory conditions, respectively, will be described.

3.2 Field Penetrometer

The penetrometer described here is of the continuous stress type. It is designed so that soil strength can be measured

continuously down to a depth of 600 mm. The penetrometer was designed by Mr. G. Wilson, former Soil Physicist in the Soil Productivity Research Team, but has been modified by the author to improve its precision and reliability. The instrument is shown in Plate 3.1 with the basic components annotated. A is a threaded shaft, driven via a gear and chain mechanism by rotating handle B. Rotation of B counter-clockwise drives the whole assembly A and C-F downwards. D is a depth marker, adjustable for zero and records penetration depth on scale G. E is the 'skin friction' shaft which houses needle shaft L. Pressure on point F acts via shaft L and plunger K on to pressure cell assembly C. The cell, which is filled with brake fluid is bounded at its 'open' end by flexible rubber membrane J, and is tapped for a tube which connects to a pressure gauge H registering 0 - 100 scale units. Point F has a maximum diameter of 13,7 mm, 25 mm long straight sides and is cone shaped at the tip with an included angle of 60^{o}. The shaft is relieved behind the point to a diameter of 6 mm.

In use the penetrometer point is wound down on to the soil surface and the depth pointer is set to zero. Gauge readings, reflecting force on the point are then noted at suitable depth increments, usually 10 mm, down the profile. The point, being relieved behind the tip registers only point resistance as it penetrates the soil.

3.2.1 Calibration

The penetrometer, by virtue of its design does not give gauge readings directly in bars, the unit used for pressure measurement. It was necessary, therefore, to establish the relationship between point pressure and gauge reading in a series of calibration measurements with the instrument. In these measurements the pressure registered on the gauge was compared with a known force acting on the penetrometer point. In order to test the long-term reproducibility of readings, calibration measurements were repeated regularly over a period of five months.

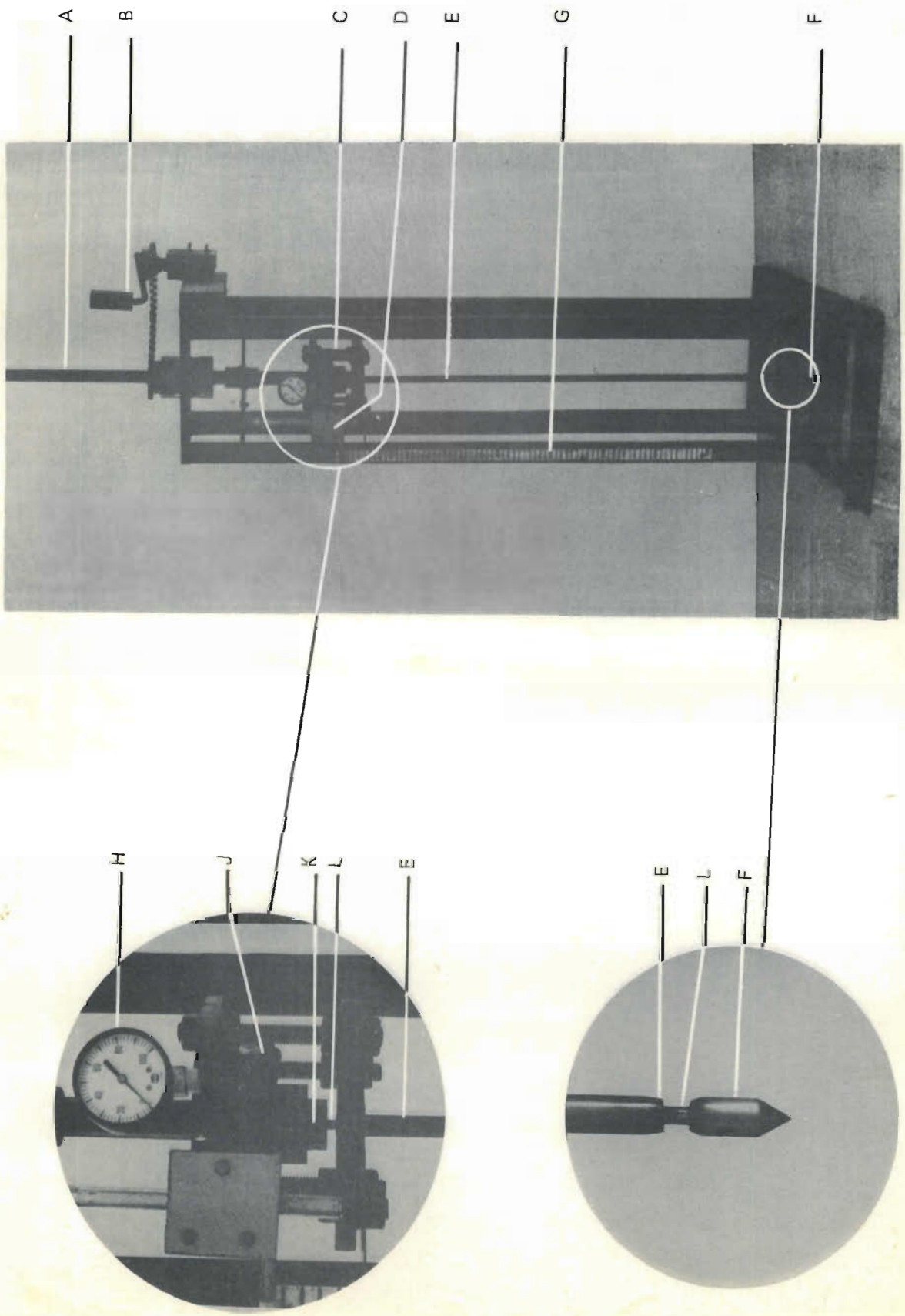


Plate 3.1 FIELD PENETROMETER

a) Procedure

In order to exert a known force on the penetrometer point, a platform scale (Avery No. 3505 AAA, 0 - 100 kg) which was placed in a hole in the ground was used. The penetrometer was then placed above this, supported by the soil on either side of the scale. Sand bags placed on the 'feet' of the penetrometer steadied it and prevented it from lifting at high point pressures. A small block of wood, drilled to accept the penetrometer point was placed on the platform of the scale which was then set to a balance point of 10 kg. The penetrometer point was wound slowly down until the balance point was reached, at which stage the penetrometer gauge was read. The platform scale was then set to 20 kg and the procedure repeated. Pressure gauge readings were made at 10 kg mass increments in turn up to 80 kg. In all, a total of 21 sets of readings (8 readings at 10 - 80 kg in each set) was made over a period of five months. Gauge readings calculated from instrument specifications and the forces acting on the penetrometer point were compared with the mean gauge readings actually measured.

b) Results

Calculated and mean measured gauge readings are shown in Table 3.1. Statistical analysis of the data showed a very highly significant linear relationship ($R^2 = 0,9996$; $P = 0,001$), between calculated and mean measured gauge readings. There was no significant difference in the regression slope with time over the measurement period. Coefficient of variation of measured gauge readings was 0,8%. (Individual mean monthly readings and analysis of variance table are shown in appendix 3.1.)

In addition to calibrating the penetrometer it was necessary to calculate a conversion factor for the instrument, so that gauge readings could be related to point pressure in bars. Using the dimensions of the point, the plunger and the gauge specifications, one scale division was calculated to represent a point pressure of 0,904 bar. Readings obtained in the field were corrected using the regression equation and conversion factor. The overall equation used to convert gauge readings to actual point pressure

(soil strength) in bars was

$$\text{Soil strength} = 0{,}904\left[1{,}001(\text{gauge reading}) - 0{,}86\right] \quad 3.1$$

TABLE 3.1

Calculated and mean gauge readings for field penetrometer measured during calibration

Platform scale setting kg	Calculated gauge reading	Mean measured reading
10	7,4	7,8
20	14,7	15,6
30	22,1	23,2
40	29,4	30,4
50	36,8	38,0
60	44,2	45,0
70	51,5	52,2
80	58,9	59,4

c) Discussion

Calibration of the penetrometer has shown a very close agreement between calculated and measured gauge readings. In addition, it has been shown that there is no significant change in the regression slope over a period of five months. Thus the instrument can be used with confidence over a period of time to measure soil strength.

3.2.2 Field measurement technique

The field penetrometer is used to characterize the presence (or absence) of hard layers in field situations. The most important single factor to take into account when measuring resistance to penetration is the strong dependence of soil strength on soil moisture (Shaw, Haise and Farnsworth, 1942, and chapters 4 and 5 of this investigation). Thus, if comparisons of soil strength are to be made between different soils, or between different treatments on a particular soil, a reproducible

soil moisture status must be chosen.

The most easily reproduced field soil moisture status is that of so-called 'field capacity'. This is a vaguely-defined concept but is taken to be the water content of a soil thoroughly wetted by irrigation or rainfall, after subsequent rate of drainage out of the profile has become negligibly small. The period of time required to reach a negligible drainage rate is arbitrarily taken as 2 days. This water content is reasonably reproducible (Baver et al., 1972). Field measurements of soil strength were therefore made 1 - 2 days after enough rain had fallen to wet the profile to the depth of sampling, generally 600 mm.

Measurements of field resistance to penetration were begun by placing the penetrometer on a firm, flat surface on the soil. The depth pointer was set to zero on the depth scale with the penetrometer tip on the soil surface. The penetrometer was steadied by one person standing on either side of it. The handle was wound at a steady rate (approximately one revolution per second) and readings were made on the pressure gauge at 10 mm depth increments (registered on the depth scale) down to a depth of 600 mm. After each profile had been completed the tip was wound up and cleaned to remove soil adhering to the shaft behind the tip.

When the penetrometer was being used to measure soil strength on the tillage trials, it soon became apparent that hard layers were present in all the profiles studied, but that individual depths to the hard layer within a particular ploughing depth treatment varied appreciably. This variation was due mainly to variations in depth of ploughing within a particular treatment. These variations presented a problem in evaluating the results of the soil strength/depth determination. This is best illustrated by the example shown in Fig. 3.1 which shows three individual soil strength/depth profiles measured on the 100 mm ploughing depth treatment at Grasslands. These profiles differ in two main ways:

a) the depth to the hard layer, and

b) the maximum soil strength in the hard layer.

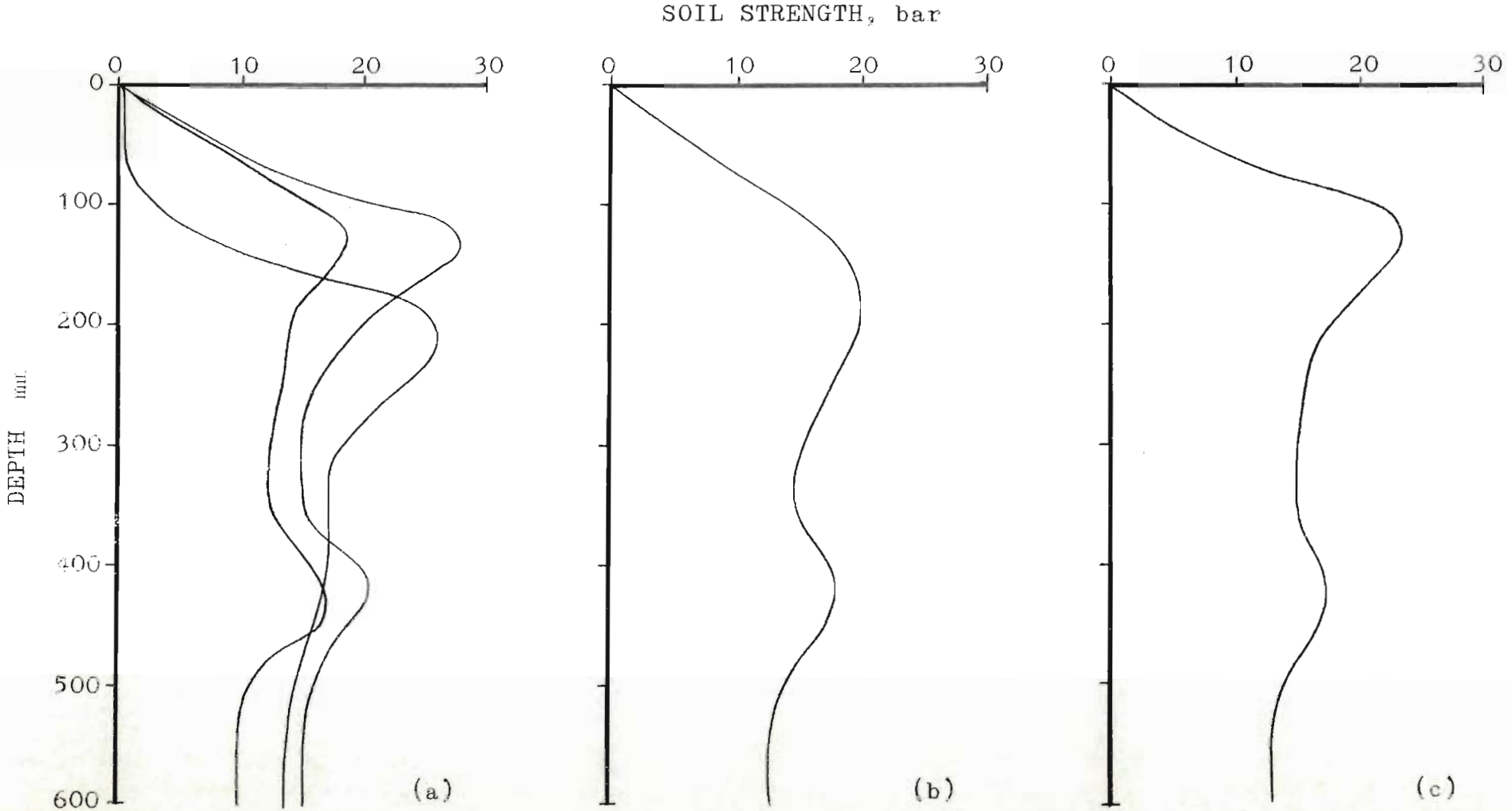


Fig. 3.1 Calculation of 'modal' profile (for explanation see text): (a) three individual soil strength/depth profiles, (b) 'mean' profile, and (c) 'modal' profile

An arithmetic mean of soil strengths at each depth for the three profiles results in the 'mean' profile shown in Fig. 3.1(b). The shape of this profile is not representative of the individual profiles; nor is the depth of the hard layer representative of the mean of the depths to the hard layer in the individual profiles. This prompted an investigation to determine the best method of representing the 'mean' profile.

Immediately above the hard layer the rate of change of soil strength with depth is high. The hard layer was therefore defined as that layer just below the zone of 'maximum rate of change of soil strength per unit depth'. Individual profiles were then aligned one with the other on their hard layers, by moving each profile either up or down with respect to the position of its hard layer. Mean depth to the hard layer was calculated as the arithmetic mean of the individual depths to the zone of 'maximum rate of change of soil strength with depth'. Mean soil strengths in the profile were then obtained by summing the individual soil strengths and taking the mean. The 'modal' profile thus calculated for the three individual profiles in Fig. 3.1(a) is shown in Fig. 3.1(c). The shape of this 'modal' profile is representative of the shapes of the individual profiles and the depth to the hard layer is the mean of the depths to the hard layer in the individual profiles.

3.3 Laboratory penetrometer

3.3.1 Introduction

A field penetrometer designed to evaluate the presence (or absence) of hard layers in field soils has been described. Evaluation of the physical factors causing hardness in these soils is better done on a much smaller scale, under carefully controlled laboratory conditions. A laboratory penetrometer, and the theory of its use will now be discussed.

3.3.2 Theory

Consider a single rigid probe penetrating a semi-infinite

body of homogeneous, compressible soil which is finely structured so that it can be treated as a statistical continuum. In such a soil the point pressure q_p[+], on the conical end or 'point' of a rigid probe in a deep test is given by

$$q_p = \sigma_N (1 + \tan \phi' \cot \alpha) \qquad 3.2$$

where $\tan \phi' \approx 0,4$ is the coefficient of soil-probe (steel) friction, and α is the included semi-angle of the penetrometer cone (Greacen, Barley and Farrell, 1968). The normal stress on the basal surface of the probe, σ_N, can be found from the strength parameters, apparent cohesion (c) and angle of internal friction (ϕ), and the compressibility coefficients of the soil. These latter parameters can be obtained from triaxial compression tests (Bishop and Henkel, 1957).

Farrell and Greacen (1966) have analysed the forces acting on the point of a metal probe. Their analysis is based on the model of spherical expansion of a cavity at the point of the probe. Compression of the soil was considered to occur in two main zones. These were a zone of compression with plastic failure surrounding the probe, and a zone of elastic compression further away. The total point resistance was assumed to be made up of the pressure component required to expand the cavity, and a point frictional component determined by the properties of the probe. For a steel probe with an included semi-angle $\alpha = 30^{\circ}$, Farrell and Greacen (1966) were able to calculate point resistance quite accurately for different soils over a wide range of conditions.

Using this model then, the theoretical and practical aspects of measurement of soil resistance with a needle penetrometer will be studied.

3.3.3 Factors affecting measurement of point resistance

Cockroft (1968) has studied in some detail the operation of penetrometers in soil and the main factors requiring consideration

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[+] q_p is defined as the resistance acting on the relieved tip of a probe, in the direction of its longitudinal axis, per unit of the maximum cross-sectional area of the tip

if satisfactory measurements of soil resistance are to be made. Consideration will be given to these factors, and a penetrometer designed on this basis will be described.

a) Rate of penetration

When a clay is deformed, consolidation and changes in pore water pressure occur (Bolt, 1956; Greacen, 1959). These are rate-dependent processes and consequently the rate of penetration can be expected to affect the resistance to penetration. Assessment of the importance of this factor is critical to an understanding of the process of penetration (Cockroft, 1968).

Cockroft measured point resistance in cores of remoulded clay at penetration rates of 0,175; 1,25; 10,0 and 60 mm h^{-1}. The results of this investigation are shown in Table 3.2. Point resistance was inversely related to rate of penetration.

TABLE 3.2

Effect of penetration rate on penetrometer resistance (after Cockroft, 1968)

Penetration rate mm h^{-1}	Point pressure bar
0,175	19,0
1,25	17,2
10,0	15,1
60,0	10,4
LSD (0,01)	2,6

When clays with a low hydraulic conductivity are compressed and sheared, pore water pressure increases due to slow redistribution of water. This reduces the shearing strength of the clay, lowering the measured point resistance. Cockroft (1968) calculated that at a penetration rate of 60 mm h^{-1} the pore water pressure in the clay he was studying increased by 3,30 bars. At a penetration rate of 0,175 mm h^{-1}, the increase was only 0,01 bar.

These results have important implications in the use of the penetrometer in soils. The rate of penetration must be related to the particular deformation under study. Thus, if probe data are to be related to root growth, conditions should be used under which there is minimal build up in pore water pressure, bearing in mind that the root absorbs water during its extension through the soil. It will therefore reduce the pore water pressure of its own accord. If penetrometers are to be used to simulate plant roots, the rate of penetration to be used should be as slow as is practicable.

Cockroft (1968) used a penetration rate of 1,25 mm h^{-1} in his study. In order to establish whether a faster rate could be used in this investigation hydraulic conductivity of Domboshawa soil was calculated from its moisture characteristic curve, using the technique of Marshall (1958). Hydraulic conductivity of this soil was in the range 0,09 to 0,71 x 10^{-3} cm s^{-1} (depending upon moisture content). The clay used by Cockroft (1968) had a calculated hydraulic conductivity in the range 0,09 to 7,7 x 10^{-9} cm s^{-1}. The faster hydraulic conductivity of Domboshawa soil therefore justifies using a faster rate of penetration than that used by Cockroft (1968).

b) Diameter of probe

Larger probes cause a greater increase in pore water pressure at a particular rate of penetration than do smaller diameter probes. The effect of probe diameter on measured point resistance in a remoulded clay is shown in Table 3.3. The difference between the two values was highly significant (P = 0,01). As small a diameter probe as is practicable should therefore be used so that the increase in pore water pressure is minimal.

TABLE 3.3

Effect of probe diameter on point resistance in a remoulded clay (after Cockroft, 1968)

Probe diameter mm	Point pressure bar
1,25	20,7
2,00	17,2

c) Shape of probe

Barley, Farrell and Greacen (1965) used a penetrometer with a conical tip (included angle 60°). This was relieved behind the point, with a friction sleeve behind the tip. (Similar, though on a much smaller scale, to the field penetrometer.) Point resistance and skin friction (friction on the shaft) could be measured independently of one another with this arrangement. Point resistance is the more important parameter. It can be measured quite simply by using a conical probe, relieved behind its point, so that most of the effect of skin friction is eliminated.

3.3.4 Penetrometer design

Considering the aforementioned factors, the basic components required for a laboratory penetrometer are:

a) a device for applying a constant (slow) rate of strain over a suitable distance;
b) a penetrometer needle, relieved behind the tip, and
c) a means of measuring the force on the needle penetrating the soil.

A compression test machine (Wykeham Farrance - Model T56) was adapted for applying a constant rate of strain. The machine applies a rate of strain of 100 mm h^{-1} over a distance of 100 mm vertically upwards. For use as a penetrometer in this study it was inverted and mounted on a stand (see Plate 3.2). An adaptor was machined to fit the ram to accommodate a drill chuck which held the penetrometer needle. The stainless steel needle had a maximum diameter of 1,5 mm at the point and was cone-shaped with an included angle of 60°. The shaft, relieved behind the tip had a diameter of 1 mm, and was 55 mm long.

Positioned below the needle was a Sartorius Model 2253 toploading balance. In use the soil core in which soil strength was to be measured was placed on the pan of the balance, which was then tared back to zero. (The balance could be tared 0 - 1 000 g in the optical range.) With the needle moving

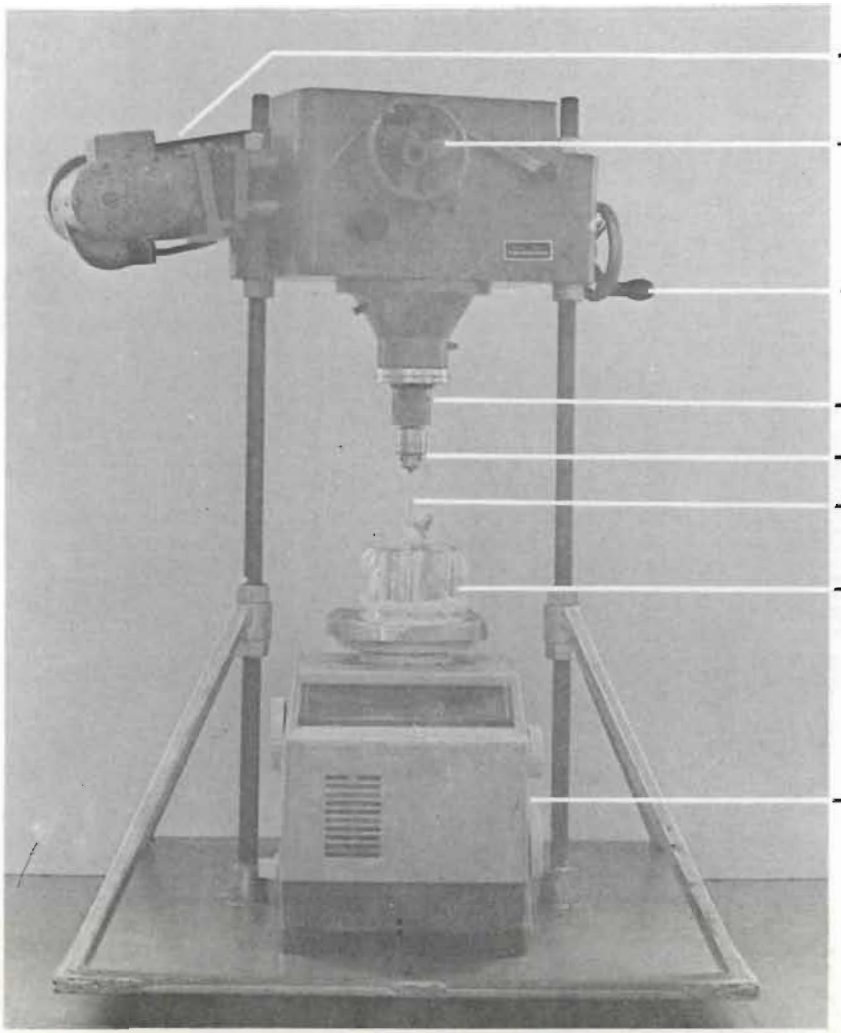

Plate 3.2 LABORATORY PENETROMETER

vertically downwards into the core, the force on the needle was registered on the balance as a mass reading. This mass reading was converted to point resistance (pressure) in bars using the equation:

$$\text{Soil strength} = 0{,}0555 \text{ (mass reading)} \qquad 3.3$$

where soil strength is in bars, and mass reading in grammes.

3.3.5 Standard measurement technique

Soil cores for soil strength measurement were equilibrated at specific matric potentials on a tension tray or on a ceramic plate in a pressure plate extractor. These cores were stored overnight in double polyethylene bags after equilibration. Before measuring soil strength the outer bag was removed, and the core placed on the pan of the balance. The balance was then tared back to zero. Using the 'coarse' feed (Plate 3.2) the penetrometer needle was wound downwards into the core to a depth of about 6 mm. This depth was chosen because Cockroft (1968) found that maximum point resistance was only expressed at depths $>4d$, where d is the diameter of the probe. The 'fine' feed was then selected and the motor turned on. A stopwatch was started simultaneously, and readings on the balance were then taken every 30 seconds (approximately 0,8 mm depth increments).

Scale readings on the balance in the range 0 - 1 000 g corresponded to point resistances of 0 - 55,5 bars. The range could be extended by placing one 200 g and one 500 g brass masspiece on the scale pan before taring back to zero. If the optical scale was exceeded during measurement, the motor was stopped, the needle wound back and one or both of the masspieces removed. The motor was then restarted and readings continued. Using this technique the range could be extended to 66,6; 83,3 or 94,4 bars. These ranges were sufficient for all practical purposes.

In all cases duplicate 'profiles' 180° apart were measured in a particular core at a specific moisture content, with the

penetrometer probe 25 mm from the edge of the core. Point resistance was measured over a depth of 50 mm in each core and soil strength was calculated as the mean of 120 individual mass readings, converted to point pressure in bars.

3.4 Summary

A continuous stress penetrometer designed to measure soil strength down to a depth of 600 mm under field conditions has been described. The instrument has been shown to maintain its accuracy over a period of time. The field measurement technique and method for calculating 'modal' profiles are described.

The theory of laboratory penetrometers, in particular the effect of penetration rate and of size and shape of probe on soil strength measurements are discussed. A laboratory penetrometer and standard technique for measuring soil strength are described.

CHAPTER 4

PHYSICAL CHARACTERISTICS OF THE TILLAGE TRIAL SOILS

4.1 Introduction

The four tillage trials studied in this investigation were established in order to examine the effects of ploughing continuously to three different depths (100, 230 and 355 mm) with two types of plough (mouldboard and disc) on maize yield. Superimposed on the ploughing depth/type of plough treatments were three different compost or, at Hatcliffe, fertilizer levels. (Full details of the four tillage trials are contained in appendix 4.1.) The major objectives of the investigations reported in this thesis were to determine the effects of the ploughing depth treatments on the physical characteristics of the soils, and the effects of the latter on root growth and maize yield.

In order to evaluate these physical characteristics, complementary field and laboratory investigations were carried out. In the field investigation soil strength/depth profiles were measured on each of the three ploughing depth treatments at the four sites. For the laboratory investigation, a comprehensive series of undisturbed cores was taken from each of the tillage trials and subjected to extensive physical measurements.

4.2 Field measurement of soil strength

Using the field penetrometer and standard measurement technique described previously (section 3.2), soil strength/depth profiles were measured at Domboshawa, Grasslands, Makoholi and Hatcliffe on the zero compost (low fertilizer at Hatcliffe) disc-ploughed plots. At Grasslands, Makoholi and Hatcliffe measurements were made the day after soaking rain had fallen, so the whole profile was at 'field capacity'. At Domboshawa, however, readings were taken two days after rain and the surface soil had been dried by evapotranspiration during two

days of bright sunshine. The soil strengths measured in the surface layers at Domboshawa were therefore not strictly comparable with those measured at the other three sites.

4.2.1 Results

Modal profiles were calculated, using the technique described in section 3.2.2, for each of the three ploughing depth treatments on the Domboshawa, Grasslands, Makoholi and Hatcliffe tillage trials. Soil strengths measured in the surface layers at Domboshawa were abnormally high. Subsequent laboratory measurement of soil strength on undisturbed cores (section 4.4.3) confirmed this observation, and the soil strengths in the surface layers of the modal profiles at Domboshawa were therefore adjusted using the laboratory data.

Modal profiles for the four tillage trials are presented in Fig. 4.1. Hard layers were present between just below and 150 mm below the nominal plough depths on all treatments at the four sites, with the exception of the 100 mm ploughing depth treatment at Hatcliffe. The hard layers all had soil strengths in the range 16 to 24 bars, with soil strengths in the 100 mm ploughing depth treatments tending to be higher at 21 to 24 bars.

4.2.2 Weighted mean soil strength

In order to provide a more meaningful method for characterizing and comparing soil strength/depth profiles, the concept of weighted mean soil strength was introduced. On the assumption that high soil strength near the soil surface would be more detrimental to root proliferation and crop yield than it would be at depth, mean soil strengths over 100 mm depth increments from the surface down to 600 mm were weighted by multiplying them in turn by 6, 5, 4, 3, 2 and 1. The products were summed and then divided by 21, the sum of the multipliers, to give the weighted mean soil strength for the particular profile. Weighted mean soil strengths for the three ploughing depth treatments on the four tillage trials are presented in Table 4.1. For the purposes of the statistical analysis the

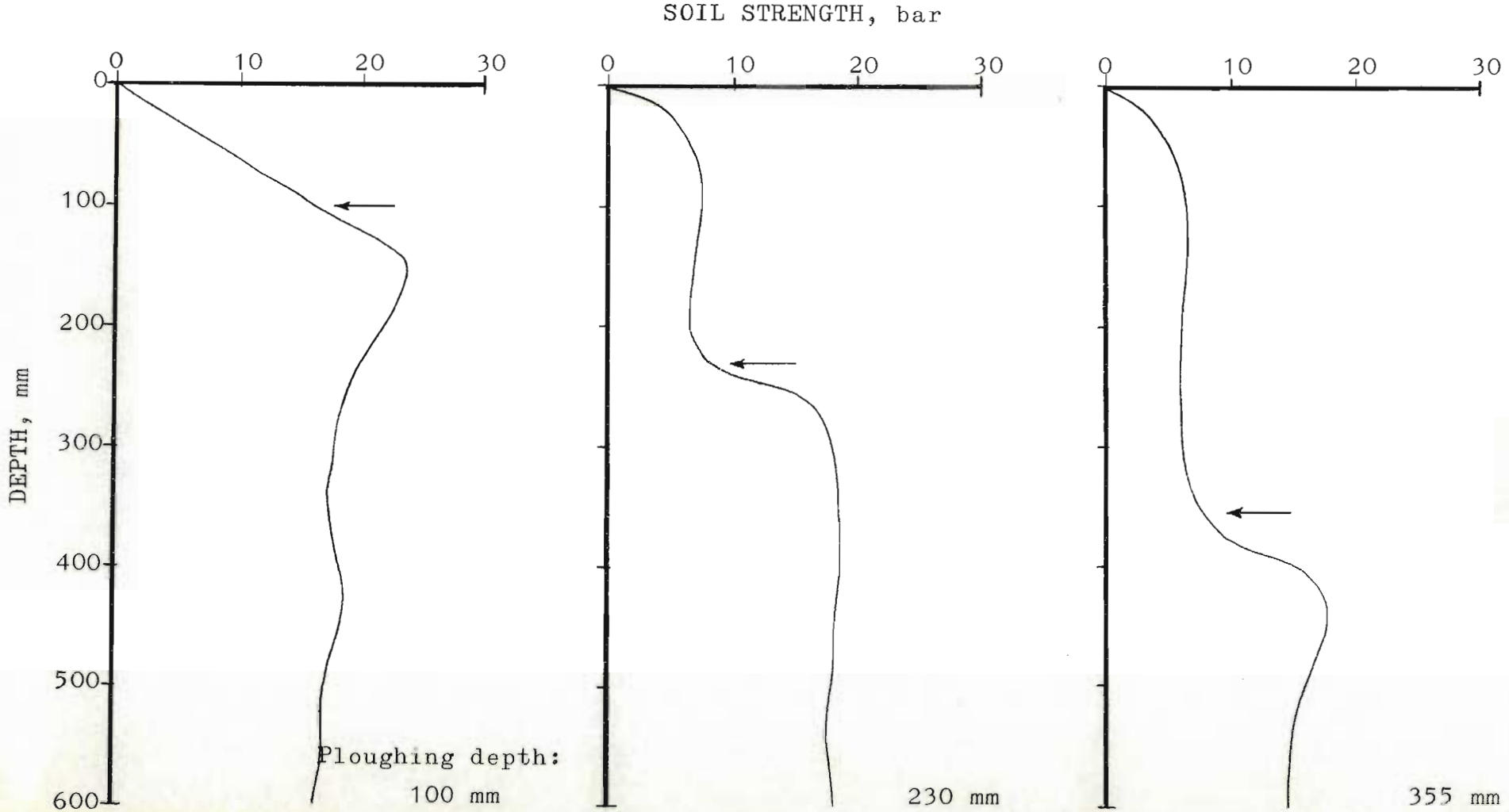

Fig. 4.1 (a) 'Modal' soil strength/depth profiles for the three depths of ploughing treatments at DOMBOSHAWA - each profile is the adjusted mean of 15 profiles from six replicates (the arrows indicate depth of ploughing)

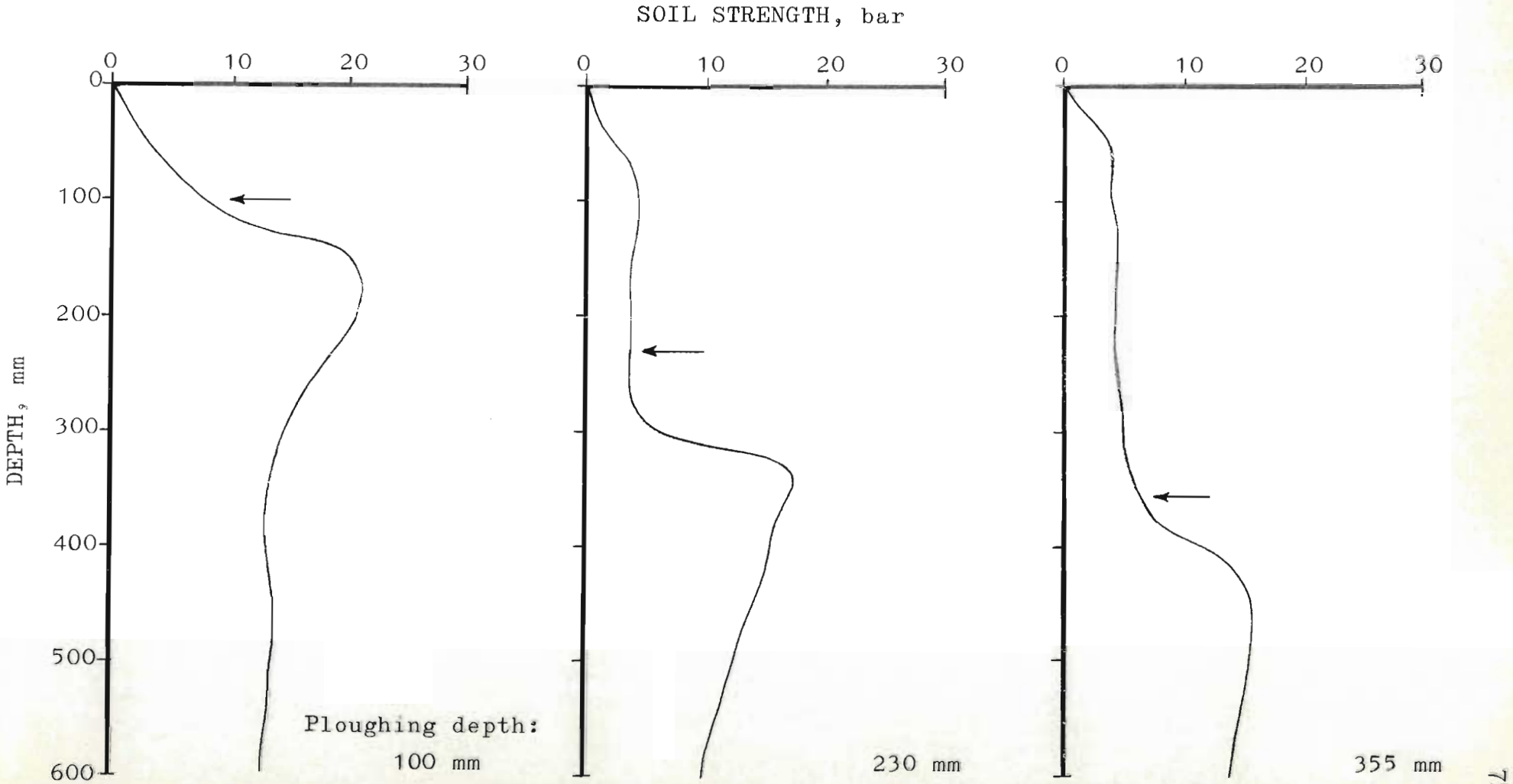

Fig. 4.1 (b) 'Modal' soil strength/depth profiles for the three depths of ploughing treatments at GRASSLANDS - each profile is the adjusted mean of 12 profiles from four replicates

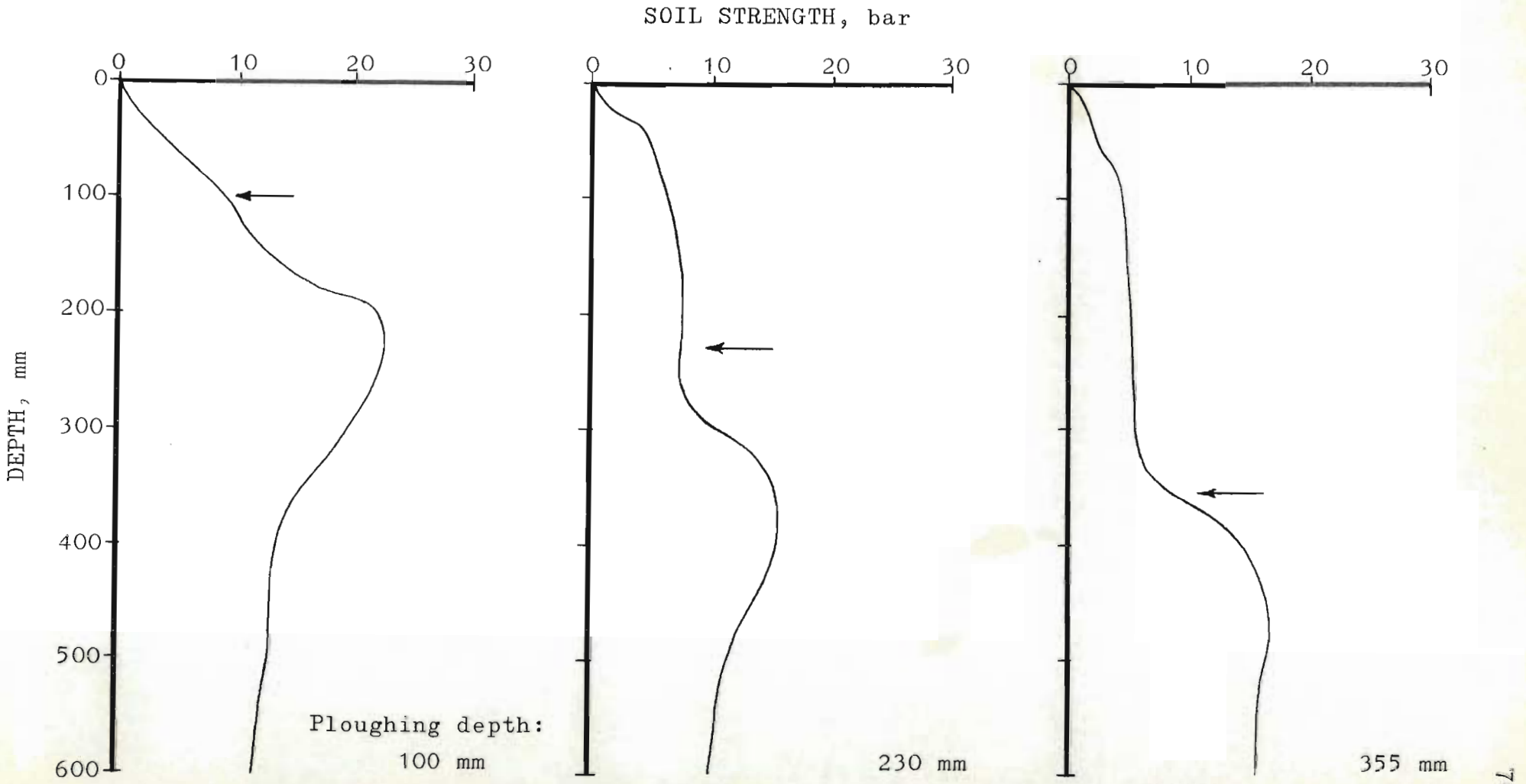

Fig. 4.1 (c) 'Modal' soil strength/depth profiles for the three depths of ploughing treatments at MAKOHOLI - each profile is the adjusted mean of six profiles from two replicates

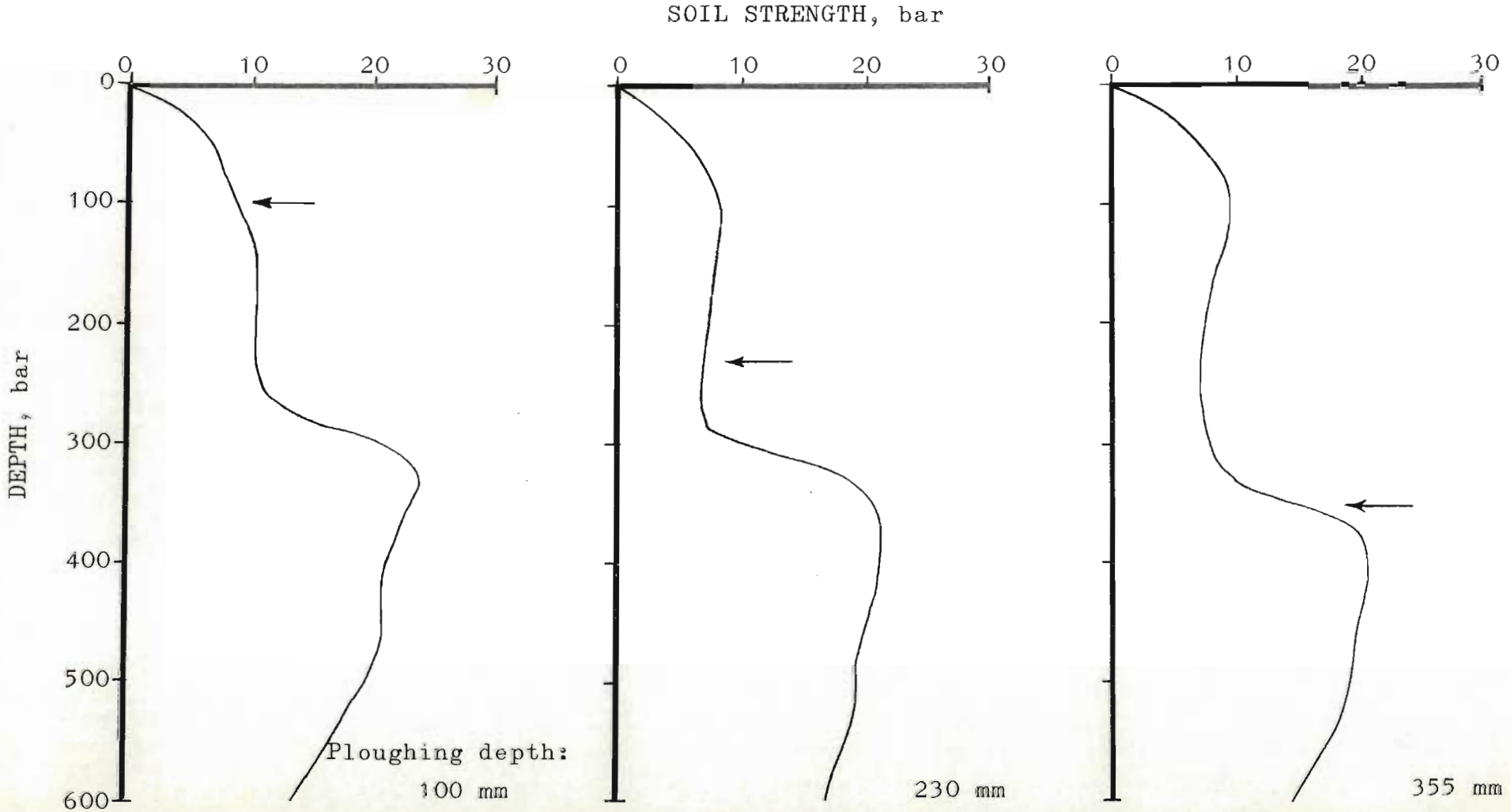

Fig. 4.1 (d) Modal soil strength/depth profiles for the three depths of ploughing treatments at HATCLIFFE - each profile is the adjusted mean of 14 profiles from six replicates

original Domboshawa soil strength data were used; weighted mean soil strengths calculated from the 'adjusted' data are shown at the foot of Table 4.1.

TABLE 4.1

Weighted mean soil strengths on the three ploughing depth treatments at Domboshawa, Grasslands, Makoholi and Hatcliffe (bars)

Ploughing depth, mm	Site			
	Domboshawa	Grasslands	Makoholi	Hatcliffe
100	19,9+	12,4	13,6	12,5
230	12,8	6,5	8,5	10,9
355	9,4	5,9	6,9	10,6
SE	0,84	0,56	0,60	0,60
LSD: 0,05	2,4	1,6	1,8	1,7
0,01	3,2	2,2	2,5	2,3
0,001	4,2	2,9	3,5	3,0
Significance	***	***	***	NS

+'adjusted' Domboshawa values:

100 mm : 16,6 bars
230 mm : 11,5 bars
355 mm : 8,0 bars

The overall ploughing depth effect on weighted mean soil strength was very highly significant at Domboshawa, Grasslands and Makoholi (coarse-textured soils), but was not significant at Hatcliffe (fine-textured soil). Weighted mean soil strengths decreased with increased depth of ploughing, with the main difference being between the 100 and 230 mm ploughing depth treatments, and little difference between the 230 and 355 mm ploughing depth treatments.

4.2.3 Depth to hard layer

Mean depths to the hard layer, as defined in section 3.2.2, for the four tillage trials are presented in Table 4.2. The overall ploughing depth effect was very highly significant at

all the sites. Individual differences between the three ploughing depth treatments at a particular site were all highly significant, with the exception of the difference between the 100 and 230 mm ploughing depth treatment at Hatcliffe which was not significant.

TABLE 4.2

Mean depth to hard layer (mm) on the three ploughing depth treatments at Domboshawa, Grasslands, Makoholi and Hatcliffe

Ploughing depth mm	Site			
	Domboshawa	Grasslands	Makoholi	Hatcliffe
100	103	120	150	290
230	248	307	307	301
355	373	388	367	347
SE	8,3	8,3	12,3	8,9
LSD: 0,05	24	24	37	25
0,01	32	32	51	34
0,001	42	42	71	45
Significance	***	***	***	***

4.2.4 Discussion

Data obtained with the field penetrometer have shown that hard layers exist in all the ploughing depth treatments on the four tillage trials, and that these hard layers have strengths of between 16 and 24 bars. At Domboshawa, Grasslands, Makoholi, and on the two deeper ploughing depth treatments at Hatcliffe, the hard layers occur between just below and 150 mm below the nominal depths of ploughing. On the 100 mm ploughing depth treatment at Hatcliffe, however, the hard layer is more than 200 mm below the nominal ploughing depth, indicating that there is no hard layer in this soil directly attributable to the imposed 100 mm ploughing depth treatment. This observation, which will assume importance when the effects of these hard layers on maize yield are considered, will be discussed in more detail once the data from the physical measurements on undisturbed

cores removed from the tillage trials have been presented.

4.3 Laboratory measurement of soil physical characteristics

Physical characteristics of the hard layers shown to be present in all the profiles studied are most likely to be:

a) high bulk density and soil strength,
b) poor aeration, due to a reduction in number of large pores, and
c) changed moisture retention curves.

In order to establish firstly, whether there were any differences in soil physical characteristics between the three ploughing depth treatments, and secondly, which physical factor or factors were most likely to affect root growth and/or maize yield, a comprehensive series of undisturbed cores was taken from each of the tillage trials. Soil strength, bulk density, moisture retention, air space and soil texture were measured in these cores.

4.3.1 Sampling procedure

Undisturbed cores, 75 mm high and 100 mm in diameter were taken from each of the three ploughing depth treatments on the disc-ploughed, zero compost plots (low fertilizer plots at Hatcliffe) at each of the four tillage trials. At Domboshawa, Grasslands and Makoholi, cores were taken at four depths on each ploughing depth treatment, so that one core was above the hard layer, two included at least part of it, and one was below it. At Hatcliffe a continuous series of six cores was taken from 75 mm down to 525 mm on each ploughing depth treatment. (Exact depths of sampling are given in appendix 4.2.) Seventy two cores were taken at both Domboshawa and Makoholi (12 cores from each of six replicates), 48 cores were taken at Grasslands (12 cores from each of four replicates) and 108 cores were taken at Hatcliffe (18 cores from each of six replicates). In addition, a series of 24 cores was taken from the hard layer of the high level of compost plots at Grasslands for comparison with the zero compost level cores.

Samples were taken in late winter. Each position sampled was wetted with approximately 30 litres of water the day before core removal, and care was taken not to compress the soil within the core during sampling. After sampling, the cores were placed in polyethylene bags to which a few drops of chloroform had been added, to prevent microbial growth, and stored at constant temperature (22 $\pm$ 1C) in the dark.

4.3.2 Measurement methods

In the laboratory the cores were trimmed to the size of the enclosing metal sleeves and a circle of cloth (poplin), of slightly larger diameter than the core was placed over the lower end of the core, held in place by a rubber band. The cores, six at a time, were then stood on filter paper (Whatman's No. 2) on a tension tray which was flooded with distilled water to a depth 5 mm below the top of the cores. The tension tray was covered and the cores were allowed to saturate for 24 hours. All equilibrations and measurements were made in a constant temperature room at 22 $\pm$ 1C.

The cores were drained successively at -20, -50 and -100 mbar matric potential, measured with respect to the bottom of the core, on the tension tray. Matric potentials of -20 and -50 mbar were chosen because of the important part pores emptying at these matric potentials play in soil aeration. A matric potential of -100 mbar is generally regarded as the best laboratory approximation for so-called 'field capacity' in coarse-textured soils, so this figure was used for the Domboshawa, Grasslands and Makoholi soils, which ranged from sandy clay loams to sands, respectively. At Hatcliffe, however, where the soils were sandy clay loams or sandy clays, the moisture contents of a series of 18 undisturbed cores removed 30 hours after saturation in the field were compared with moisture contents of the cores equilibrated in the laboratory. There was no significant difference between the 'field capacity' and -200 mbar water contents.

Drainage time on the tension tray was between 24 and 48 hours, and the cores were weighed after each equilibration.

Before replacing the cores on the tension tray, each core position was wetted with 10 cm^3 of water to ensure good core-tray contact. After equilibration at -100 mbar matric potential, the Hatcliffe cores were transferred to a pressure plate extractor and equilibrated at -200 mbar for 48 hours. Silica flour suspension placed on the ceramic plates improved core-plate contact and shortened drainage time considerably.

Once the cores had been equilibrated at 'field capacity' they were weighed, placed inside double polyethylene bags and stood overnight. Soil strength was then measured in duplicate profiles 180^{o} apart, with the penetrometer probe 25 mm from the edge of the core. Using the standard measurement technique described in 3.3.5, a total of 120 individual point resistance readings was taken in each core and converted to soil strength in bars.

The cores were then transferred to a pressure plate extractor and equilibrated at -1 000 mbar for 48 hours. Again, after equilibration and weighing the cores were allowed to stand overnight in double polyethylene bags before measuring soil strength. Once soil strength had been measured at -1 000 mbar, the cloth and rubber band were removed and weighed. The cores were then dried in a forced-draught oven at 105C for 48 hours, weighed, and assuming a standard volume for all the core cylinders, bulk density was calculated. The core samples were then ground gently to pass a 2 mm screen and subsampled for measurement of -5 bar water content in a pressure membrane extractor, and for particle size distribution analysis. The latter was carried out using the Bouyoucos hydrometer technique as described by Thompson (1965).

Assuming a soil particle density of 2,65 g cm^{-3}, air spaces at -20, -50 and -100 mbar (-200 mbar at Hatcliffe) were calculated. Water contents at -100 mbar (-200 mbar at Hatcliffe) and -5 bar were also calculated.

4.4 Results

Data for each of the physical factors measured were analysed statistically to test whether there was any difference in the parameter being measured with depth of sampling. Results for each physical parameter will be presented in turn.

4.4.1 Soil texture

Detailed particle size distribution results for the soils from the four sites are shown in appendix 4.3, together with their textural classes. Clay content was highest at Hatcliffe, and decreased in the order Domboshawa, Grasslands and Makoholi, with clay content at Makoholi being very low. In all the profiles there was an increase in clay content down the profile.

Hilton (1963) found that of all the particle size classes, particles $\lesssim 30$ µm in diameter were predominantly important in determining soil resistance to penetration. A combined silt plus clay figure, which included all particles ≤ 20 µm was therefore used in this investigation. Silt plus clay data for the four trial sites are presented in Table 4.3. There was a significant increase in silt plus clay percentage with depth of sampling in all the profiles, with quite a sharp change between cores taken within the plough layer, and those taken below it. This was particularly noticeable at Hatcliffe. There was some evidence of fine particles being brought up from below by deep ploughing at Domboshawa, but this was not apparent at the other three sites.

4.4.2 Bulk density

Mean bulk density values for the four soils are shown in Table 4.4. In general, bulk density was highest in the hard layer, and decreased slightly above and below it. Bulk densities within the hard layer of the shallowest ploughed plots were generally higher than those at the other two ploughing depths. This latter observation concurs with the field penetrometer measurements discussed in section 4.2.1. Overall, bulk densities were highest at Makoholi (coarse-textured soil) and lowest at

TABLE 4.3(a)

Mean silt plus clay content (%) at Domboshawa, Grasslands and Makoholi

Depth of sample	DOMBOSHAWA			GRASSLANDS			MAKOHOLI		
	Ploughing depth, mm			Ploughing depth, mm			Ploughing depth, mm		
	100	230	355	100	230	355	100	230	355
1	15,3	17,0	18,8	12,3	16,2	15,1	4,8	4,6	5,4
2	16,7	21,0	18,9	14,4	17,8	15,1	4,8	5,0	5,6
3	24,5	28,8	26,5	17,4	22,7	22,8	5,5	5,7	6,2
4	30,1	29,2	28,7	20,9	22,9	22,7	5,7	6,0	6,5
SE	0,93	1,37	0,85	0,47	0,53	1,74	0,16	0,18	0,18
LSD: 0,05	2,8	4,1	2,6	1,5	1,7	5,6	0,5	0,5	0,5
0,01	3,9	5,7	3,6	2,2	2,4	8,0	0,7	0,8	0,8
0,001	5,4	7,9	4,9	3,2	3,6	11,8	0,9	1,0	1,0
Significance[+]	***	***	***	***	***	*	**	***	**

[+]significance of depth of sampling effect

Hatcliffe (fine-textured soil).

TABLE 4.3(b)

Mean silt plus clay content (%) at Hatcliffe

Depth of sample		Ploughing depth, mm 100	230	355
1		40,8	40,4	40,7
2		41,2	39,4	40,0
3		45,1	41,3	40,9
4		46,9	45,5	41,7
5		50,4	49,3	47,5
6		49,6	49,3	48,4
SE		0,77	0,73	0,52
LSD:	0,05	2,2	2,1	1,5
	0,01	3,0	2,9	2,1
	0,001	4,1	3,9	2,8
Significance		***	***	***

Bulk densities in the surface layers at Makoholi, particularly in the two deeper ploughing treatments, were higher than those in the cores immediately below. Willatt (Agric. Res. Council of C. A. Ann. Rept., 1967) found at Grasslands that there was a definite increase in bulk density of the soil as the season progressed, the most noticeable increases being in the surface soils, but gave no explanation for this. It could be due to settling of the soil under the influence of raindrop action and alternate wetting and drying. The latter process has been shown by Gerard, Cowley, Burleson and Bloodworth (1962) to result in close-packing of a soil, particularly in the zone 75 to 175 mm below the soil surface.

4.4.3 Soil strength

Mean soil strengths measured at -100 and -1 000 mbar matric potential at Domboshawa, Grasslands and Makoholi, and at -200 and -1 000 mbar at Hatcliffe are shown in Table 4.5. Soil strengths in a particular soil were closely correlated with

TABLE 4.4(a)

Effect of ploughing depth and depth of sampling on mean bulk density ($g\ cm^{-3}$) at Domboshawa, Grasslands and Makoholi

Depth of sample	DOMBOSHAWA			GRASSLANDS			MAKOHOLI		
	Ploughing depth, mm			Ploughing depth, mm			Ploughing depth, mm		
	100	230	355	100	230	355	100	230	355
1	1,54	1,41	1,37	1,48	1,41	1,36	1,60	1,63	1,65
2	1,62	1,40	1,41	1,55	1,45	1,38	1,64	1,60	1,62
3	1,53	1,45	1,49	1,50	1,43	1,48	1,60	1,63	1,63
4	1,46	1,42	1,46	1,43	1,37	1,43	1,59	1,61	1,61
SE	0,024	0,023	0,024	0,023	0,052	0,020	0,014	0,014	0,017
LSD: 0,05	0,07	0,07	0,07	0,07	0,17	0,06	0,04	0,04	0,05
0,01	0,10	0,10	0,10	0,11	0,24	0,09	0,06	0,06	0,07
0,001	0,14	0,13	0,14	0,16	0,35	0,14	0,08	0,08	0,10
Significance	**	NS	**	*	NS	**	NS	NS	NS

TABLE 4.4(b)

Effect of ploughing depth and depth of sampling on mean bulk density (g cm^{-3}) at Hatcliffe

Depth of sample		Ploughing depth, mm 100	230	355
1		1,17	1,18	1,18
2		1,22	1,17	1,14
3		1,26	1,21	1,14
4		1,25	1,23	1,20
5		1,25	1,23	1,22
6		1,22	1,20	1,20
SE		0,021	0,022	0,019
LSD:	0,05	0,06	0,06	0,05
	0,01	0,08	0,09	0,07
	0,001	0,11	0,12	0,10
Significance		NS	NS	*

the bulk densities presented in the previous section, however, at a specified bulk density and matric potential soil strengths in each of the four soils were quite different. This point will be studied more closely in chapter 5.

Soil strengths measured at 'field capacity' (-100 mbar at Domboshawa, Grasslands and Makoholi, and -200 mbar at Hatcliffe) in the laboratory showed the same pattern as those measured at 'field capacity' with the field penetrometer. Thus field-measured strengths of the hard layer (section 4.2.1) were in the range 16 - 24 bars, while those measured in the laboratory were in the range 15 - 23 bars. The laboratory measurements showed a similar trend to the field measurements in that soil strengths in the hard layers of the shallow-ploughed (100 mm) treatments were higher than those in the deeper-ploughed treatments.

Mean soil strengths at -1 000 mbar matric potential on the three coarse-textured soils were between 71 and 62% higher than those measured at -100 mbar, and were ranked in the same order as mean silt plus clay content. Thus Domboshawa (mean

TABLE 4.5 (a)

Effect of ploughing depth, depth of sampling and matric potential on mean soil strength (bar) at Domboshawa

Depth of sample	Ploughing depth, mm					
	100		230		355	
	-100 mbar	-1 000 mbar	-100 mbar	-1 000 mbar	-100 mbar	-1 000 mbar
1	16,1	27,0	9,1	16,3	6,1	12,2
2	22,8	40,4	8,9	15,1	7,6	11,2
3	18,9	32,6	17,0	26,9	18,8	31,1
4	18,8	33,0	16,8	31,2	15,1	25,3
SE	2,97	5,02	2,57	3,35	1,59	2,33
LSD: 0,05	9,0	15,1	7,8	10,1	4,8	7,0
0,01	12,4	20,9	10,7	14,0	6,6	9,7
0,001	17,1	28,9	14,8	19,3	9,2	13,4
Significance	NS	NS	NS	**	***	***

TABLE 4.5(b)

Effect of ploughing depth, depth of sampling and matric potential on mean soil strength (bar) at Grasslands

Depth of sample	Ploughing depth, mm					
	100		230		355	
	-100 mbar	-1 000 mbar	-100 mbar	-1 000 mbar	-100 mbar	-1 000 mbar
1	11,2	17,4	11,8	19,1	7,7	11,0
2	17,8	30,6	14,4	26,7	7,7	10,1
3	18,0	27,7	16,9	28,5	19,3	32,1
4	14,7	24,0	12,1	21,4	14,9	30,1
SE	2,71	4,18	4,42	8,66	0,81	2,55
LSD: 0,05	8,7	13,4	14,2	27,7	2,6	8,2
0,01	12,5	19,2	20,3	39,8	3,7	11,7
0,001	18,3	28,3	29,9	58,6	5,5	17,2
Significance	NS	NS	NS	NS	***	***

TABLE 4.5(c)

Effect of ploughing depth, depth of sampling and matric potential on mean soil strength (bar) at Makoholi

Depth of sample	Ploughing depth, mm					
	100		230		355	
	-100 mbar	-1 000 mbar	-100 mbar	-1 000 mbar	-100 mbar	-1 000 mbar
1	15,2	26,8	16,9	32,0	20,7	48,4
2	17,9	25,8	15,3	19,1	14,3	22,4
3	13,7	20,0	17,1	23,3	15,5	25,7
4	12,6	17,7	15,4	22,6	15,6	22,8
SE	1,71	2,51	1,78	1,90	1,96	2,53
LSD: 0,05	5,2	7,6	5,4	5,7	5,9	7,6
0,01	7,1	10,5	7,4	7,9	8,2	10,5
0,001	9,8	14,5	10,3	10,9	11,3	14,6
Significance	NS	NS	NS	**	NS	***

TABLE 4.5(d)

Effect of ploughing depth, depth of sampling and matric potential on mean soil strength (bar) at Hatcliffe

Depth of sample	Ploughing depth, mm					
	100		230		355	
	-200 mbar	-1 000 mbar	-200 mbar	-1 000 mbar	-200 mbar	-1 000 mbar
1	10,0	14,2	11,5	16,0	11,6	15,3
2	12,1	17,6	9,1	13,6	9,3	14,3
3	17,9	21,4	9,9	15,3	9,3	13,6
4	18,8	26,7	15,3	20,4	10,1	13,6
5	20,3	26,7	15,5	22,3	13,5	18,9
6	17,6	23,8	15,6	22,5	15,0	20,1
SE	1,42	1,72	1,35	1,82	1,25	1,54
LSD: 0,05	4,1	5,0	3,9	5,3	3,7	4,5
0,01	5,6	6,8	5,3	7,2	4,9	6,1
0,001	7,5	9,1	7,1	9,6	6,6	8,1
Significance	***	***	**	**	*	*

silt plus clay - 23,0%) had an increase on drying of 71%, Grasslands (mean silt plus clay - 18,3%) increased 67%, and Makoholi (mean silt plus clay - 5,5%) increased 62%. However, at Hatcliffe, where the mean silt plus clay content was 44,4%, mean soil strength was 39% higher at -1 000 mbar than at -200 mbar. Reasons for these observed drying effects will be discussed in more detail in chapter 5.

4.4.4 Air space

Air space was measured at -20, -50, -100 mbar, and at Hatcliffe at -200 mbar matric potential. In chapter 2 it was shown that oxygen flux index was closely correlated with air space in the range 3 - 15% air space. Thus, air space, by virtue of its close relationship to oxygen flux index can be used as an index of aeration status of a soil. Ten per cent air space, corresponding in this investigation to an oxygen flux index of approximately 20 $\mu g\ m^{-2}\ s^{-1}$ is generally regarded as being the lower limit for root proliferation (Baver *et al.*, 1972).

Results of the air space measurements will be discussed in turn for each of the four trials.

a) Domboshawa

Air space results for each of the three matric potentials are shown in Table 4.6. In general, air space was high in the surface and decreased with depth of sampling, due to the concomitant increase in silt plus clay content down the profile. Air space increased quite sharply on desaturation, particularly in the soil above the hard layer, so that even at -50 mbar air space in the ploughed soil was above 20% in all three ploughing depth treatments. Within the hard layer desaturation did not bring about as great an increase in air space, because the soil in this layer was more compact, and there were relatively fewer large pores. Air space was, however, always above 10%.

b) Grasslands

Air space results for Grasslands are presented in Table 4.7. A similar pattern to that observed at Domboshawa emerges, and

TABLE 4.6

Effect of ploughing depth, depth of sampling and matric potential on mean air space (%) at Domboshawa

Depth of sample	Ploughing depth, mm								
	100			230			355		
	Matric potential, mbar			Matric potential, mbar			Matric potential, mbar		
	-20	-50	-100	-20	-50	-100	-20	-50	-100
1	13,6	21,4	24,1	13,2	24,8	28,6	16,0	27,5	31,3
2	12,6	16,5	18,6	17,1	23,5	25,9	14,8	24,1	27,4
3	13,1	16,1	17,8	12,8	16,0	18,0	11,6	15,5	17,8
4	12,3	15,1	16,9	12,7	16,3	18,5	10,7	14,0	16,2
SE	0,84	1,16	1,26	1,11	1,58	1,69	1,20	1,46	1,51
LSD: 0,05	2,5	3,5	3,8	3,3	4,8	5,1	3,6	4,4	4,6
0,01	3,5	4,8	5,3	4,6	6,6	7,0	5,0	6,1	6,3
0,001	4,8	6,7	7,3	6,4	9,1	9,7	6,9	8,4	8,7
Significance	NS	**	**	*	**	***	*	***	***

TABLE 4.7

Effect of ploughing depth, depth of sampling and matric potential on mean air space (%) at Grasslands

Depth of sample	Ploughing depth, mm								
	100			230			355		
	Matric potential, mbar			Matric potential, mbar			Matric potential, mbar		
	-20	-50	-100	-20	-50	-100	-20	-50	-100
1	14,4	26,1	29,9	10,0	23,8	28,8	14,8	28,2	32,5
2	14,7	22,8	25,9	12,6	21,9	26,1	14,1	26,7	31,8
3	15,0	22,9	26,4	13,3	19,7	23,9	11,0	16,2	20,4
4	15,2	21,9	25,8	12,8	20,1	25,3	11,8	18,5	23,1
SE	0,67	0,46	0,60	1,28	2,37	1,27	0,82	0,90	1,02
LSD: 0,05	2,1	1,5	1,9	4,1	7,6	4,1	2,6	2,9	3,3
0,01	3,1	2,1	2,8	5,9	10,9	5,8	3,8	4,2	4,7
0,001	4,5	3,1	4,1	8,7	16,0	8,6	5,5	6,1	6,9
Significance	NS	***	**	NS	NS	**	*	***	***

air space within the ploughed layer, particularly at -50 and -100 mbar is high. Within the hard layer aeration was adequate, air space being above 11% at -20 mbar, and above 25% at -100 mbar matric potential. Overall increases in air space on desaturation were greater than those at Domboshawa, due to the coarser texture of the Grasslands soil.

c) Makoholi

Air space results for Makoholi are presented in Table 4.8. Air space at -20 mbar matric potential was in the range 9 - 14%, but increased sharply on draining to -50 mbar to be above 20% in all layers. Air spaces at -50 and -100 mbar were considerably higher than those at Domboshawa and Grasslands due to the very low silt plus clay content. There was little change in air space with depth of sampling, due to the relatively small change in silt plus clay content down the profile (Table 4.1).

d) Hatcliffe

Air space data for Hatcliffe at -20, -50 and -200 mbar matric potential are presented in Table 4.9. In general air space was higher in the surface cores than at depth, and there was little difference between air space within the hard layer and that above and below it. At -20 mbar air spaces were between 9 and 13%. Within the ploughed zone air space increased quite sharply on desaturation, though not as sharply as in the coarse-textured soils, so that it was above 20% at 'field capacity'. In the unploughed zone the increase in air space on desaturation was quite small, due mainly to the higher silt plus clay content within this zone.

Thus, overall it would seem that aeration status of these soils is adequate for root proliferation. In general, air spaces were lowest within the hard layer or at depth, but nevertheless were all above 14% at 'field capacity' within these zones. Within the ploughed zone aeration increased rapidly on desaturation, so that by the time the soils had drained to 'field capacity' air space within the ploughed zone was above 20% in all the soils.

TABLE 4.8

Effect of ploughing depth, depth of sampling and matric potential on mean air space (%) at Makoholi

Depth of sample	Ploughing depth, mm								
	100			230			355		
	Matric potential, mbar			Matric potential, mbar			Matric potential, mbar		
	-20	-50	-100	-20	-50	-100	-20	-50	-100
1	12,0	24,8	29,5	12,2	23,5	28,1	14,4	21,4	25,3
2	11,3	24,0	29,1	11,3	25,3	30,4	9,3	23,2	29,4
3	12,2	26,7	30,6	11,9	24,9	29,3	12,1	24,9	29,0
4	12,8	27,1	30,9	14,2	26,3	30,1	14,1	26,3	29,9
SE	0,91	0,77	0,61	0,94	0,98	0,83	0,65	0,90	0,81
LSD: 0,05	2,7	2,3	1,8	2,8	3,0	2,5	2,0	2,7	2,4
0,01	3,8	3,2	2,5	3,9	4,1	3,5	2,7	3,8	3,4
0,001	5,2	4,4	3,5	5,4	5,6	4,8	3,7	5,2	4,7
Significance	NS	*	NS	NS	NS	NS	***	*	**

TABLE 4.9

Effect of ploughing depth, depth of sampling and matric potential on mean air space (%) at Hatcliffe

Depth of sample	Ploughing depth, mm								
	100			230			355		
	Matric potential, mbar			Matric potential, mbar			Matric potential, mbar		
	-20	-50	-200	-20	-50	-200	-20	-50	-200
1	12,6	18,2	22,5	11,7	18,0	23,1	12,1	17,5	22,9
2	12,9	16,9	20,6	12,2	18,8	23,9	11,5	19,5	25,1
3	10,9	13,2	15,8	11,6	16,5	20,4	12,9	19,9	25,1
4	10,7	12,5	14,7	11,5	14,5	17,5	9,6	15,7	20,3
5	10,5	12,1	14,6	10,9	12,9	15,5	9,9	14,0	17,7
6	10,6	12,4	15,2	11,4	13,6	16,4	11,8	14,6	17,6
SE	1,10	1,20	1,25	0,94	1,44	1,53	0,98	1,23	1,31
LSD: 0,05	3,2	3,5	3,6	2,7	4,2	4,5	2,8	3,6	3,8
0,01	4,3	4,7	4,9	3,7	5,7	6,0	3,9	4,9	5,2
0,001	5,8	6,3	6,6	5,0	7,6	8,1	5,2	6,5	6,9
Significance	NS	**	***	NS	*	**	NS	**	***

4.4.5 Available soil moisture

This was calculated as the difference between the amount of water held at 'field capacity' (-100 mbar at Domboshawa, Grasslands and Makoholi, and -200 mbar at Hatcliffe) and at -5 bar, to a depth of 450 mm expressed in mm. This was used as an index of water available to the plant. (No attempt has been made to equate this value to the total available moisture.) Statistical analysis was performed on the data to see if there was any significant difference in available soil moisture between the three ploughing depth treatments at each of the four sites. The results are presented in Table 4.10.

TABLE 4.10

Effect of ploughing depth on available soil moisture to 450 mm (mm) at Domboshawa, Grasslands, Makoholi and Hatcliffe

Ploughing depth mm	Site			
	Domboshawa	Grasslands	Makoholi	Hatcliffe
100	35,3	31,6	29,3	38,6
230	34,8	38,4	30,1	40,4
355	33,6	34,6	33,6	41,5
SE	0,58	1,43	0,85	0,76
LSD: 0,05	1,8	5,0	2,7	2,4
0,01	2,6	7,5	3,8	3,4
0,001	3,8	12,1	5,5	4,9
Significance	NS	*	*	NS

At Domboshawa there was a small non-significant decrease in available moisture with increased ploughing depth, while at Makoholi and Hatcliffe there were small increases (significant at Makoholi) with increased depth of ploughing. Available moisture at Grasslands was highest on the 230 mm ploughing depth treatment and least on the 100 mm ploughing depth treatment, with the overall effect significant. The overall effect of ploughing depth on available moisture was quite small.

Available moisture was highest at Hatcliffe (fine-textured soil) and lowest at Makoholi (coarse-textured soil), with Domboshawa and Grasslands intermediate. This concurs with the findings of Hensley (1969) who reported a strong positive correlation between available moisture and silt plus clay content.

4.4.6 Compost effects on the hard layer

The physical parameters described previously were compared in a series of cores taken at the same depths from the hard layer on the zero and 10 t ha^{-1} compost plots of the three ploughing depth treatments at Grasslands. Direct effects of the compost on the hard layer would be impossible, as the compost was incorporated into the ploughed zone above the hard layer. The only differences which could arise would be due to indirect effects, by the movement of soluble materials into the hard layer, or by the stimulation of greater root growth within the hard layer. None of the physical parameters measured, however, differed significantly between the zero and high compost level plots. Thus it can be concluded that added compost had no significant effect on the measured physical parameters within the hard layer.

4.4.7 Discussion

The physical parameters considered most likely to cause restricted rooting and/or crop yield, viz. bulk density, soil strength, soil aeration and available moisture have been measured in each of the four tillage trials.

Soil aeration would seem to be a problem only at high matric potentials ($>$ -20 mbar), within the hard layer or at depth. In these situations the number of large air-filled pores (the pores most important for good soil aeration) is reduced by being filled with water, by compaction or by the increased silt plus clay content, respectively. Nevertheless, air space in all cases was above 9% at -20 mbar, and above 14% at 'field capacity'. Within the ploughed zone air space increased rapidly on desaturation, so that at 'field capacity' air space in this zone was above 20% in all the soils. Thus

it is unlikely that soil aeration, even in the fine-textured Hatcliffe soil is a problem.

The effect of ploughing depth on available moisture, although significant at Grasslands and Makoholi, was quite small. The differences in available moisture between the different sites were, however, greater and this could have had some bearing on crop yield. Thus Makoholi had the lowest available moisture, Hatcliffe the highest, and Domboshawa and Grasslands were intermediate.

In general, bulk densities within the hard layers were higher than those above or below them. There was, however, a big difference between bulk densities within the hard layers at each of the four sites. Thus at Hatcliffe bulk densities within the hard layers were approximately 1,25 g cm^{-3}, while at Makoholi they were approximately 1,63 g cm^{-3}. This means that, while bulk density may be a sensitive indicator of a particular soil's resistance to penetration by roots, its usefulness is reduced when comparisons are made between different soils.

Taylor and Gardner (1963) and Taylor and Burnett (1964), working with sandy soils, found a very strong correlation between soil strength and root penetration, and concluded that it was soil strength, not bulk density that was the critical impedance factor controlling root penetration in the soils they studied. Soil strength measurements in the tillage trials studied in this investigation show the existence of hard layers within the soils, and on the evidence presented it is probably these high strength layers, rather than any other soil physical factor which controls root growth in these soils.

Soil physical factors which affect soil strength will be considered in chapter 5.

4.5 Summary

Measurements with the field penetrometer have shown that

hard layers exist in all the ploughing depth treatments on the four tillage trials. With the exception of the shallowest ploughing depth at Hatcliffe, where there is no hard layer directly attributable to the ploughing treatment, the hard layers occur between just below and about 150 mm below the nominal ploughing depths.

Physical measurements in the laboratory on undisturbed cores taken from the tillage trials indicate that high soil strength is the soil physical factor most likely to hinder root growth in these soils.

CHAPTER 5

PHYSICAL FACTORS AFFECTING SOIL STRENGTH

5.1 Introduction

Soil strength, as measured by the resistance of a soil to the penetration of a probing instrument (penetrometer) is an integrated index of several complex physical and physico-chemical processes occurring in the soil at the time of measurement. On a more general basis, though, the most important physical factors affecting soil strength are (Baver *et al.*, 1972):

a) bulk density,
b) soil moisture,
c) soil texture, and
d) clay type.

In order to evaluate some of the effects of these physical factors on soil strength, data from two sources were studied. Firstly, data for disturbed soils obtained from the literature or by personal communication, and secondly, data obtained from the undisturbed cores taken from the tillage trials were analysed in order to establish relationships between the soil physical parameters and soil strength.

5.2 Data from the literature

Much work has been done on the effects of bulk density and soil moisture on soil strength in disturbed soils. Selected data obtained from the literature or by personal communication were fitted into the multiple regression relation:

$$q_p = b_1 \ln \rho_b + b_2 \psi_m + c \qquad 5.1$$

where q_p = soil strength (bar), ρ_b = bulk density (g cm^{-3}); ψ_m = matric potential (bar), and b_1 and b_2 are the partial regression coefficients. Regression equations were calculated and the significance of the overall and partial regression

coefficients were tested (Snedecor, 1962).

Data studied were:

a) Taylor, Roberson and Parker (1966). These authors worked with four soils;

i) Miles loamy fine sand. Data were obtained from their Fig. 1. Soil strength was measured at five bulk densities (1,55 to 1,85 g cm^{-3}) at four matric potentials (-200 to -1 000 mbar).

ii) Naron fine sandy loam. Data were provided by Taylor (1974). Soil strength was measured at five bulk densities (1,55 to 1,85 g cm^{-3}) at three matric potentials (-200 to -667 mbar).

iii) Quinlan very fine sandy loam. Data supplied by Taylor (1974). Soil strength was measured at five bulk densities (1,55 to 1,85 g cm^{-3}) at -200 mbar, at four bulk densities (1,55 to 1,80 g cm^{-3}) at -333 mbar and at three bulk densities (1,55 to 1,75 g cm^{-3}) at -500 mbar matric potential.

iv) Columbia loam. Data supplied by Taylor (1974). Soil strength was measured at five bulk densities (1,25 to 1,55 g cm^{-3}) at four matric potentials (-200 to -667 mbar).

b) Taylor and Gardner (1963). Data supplied by Taylor (1974). Soil strength was measured at five bulk densities (1,55 to 1,85 g cm^{-3}) at four matric potentials (-200 to -667 mbar) in Amarillo fine sandy loam.

c) Barley et al., (1965). Data were obtained from their Table 1. Soil strength was measured at three bulk densities (1,50 to 1,70 g cm^{-3}) at two matric potentials (-300 and -700 mbar) in a Parafield loam.

Calculated regression equations and significances of the overall and partial regression coefficients are shown in Table 5.1. These data cover a wide range of soil textures (17 to 56% silt plus clay) and bulk densities (1,25 to 1,85 g cm^{-3}), while the matric potential range covers that which is most important for plant growth. The high R^2 values ($0,775 \leq R^2 \leq 0,969$) show that most of the variability in soil strength

is attributable to variations in bulk density and matric potential.

TABLE 5.1

Calculated multiple regression functions and significance levels for relation: $q_p = b_1 \ln \rho_b + b_2 \psi m + c$

Soil[+]	Calculated regression equation	R^2
Miles[1]	$q_p = 96,63^{***} \ln \rho_b - 14,16^{***} \psi m - 44,73$	0,893***
Naron[2]	$q_p = 118,76^{***} \ln \rho_b - 24,46^{***} \psi m - 56,30$	0,911***
Quinlan[2]	$q_p = 159,41^{***} \ln \rho_b - 36,21^{*} \psi m - 77,18$	0,775***
Columbia[2]	$q_p = 61,70^{***} \ln \rho_b - 9,01^{***} \psi m - 11,60$	0,943***
Amarillo[2]	$q_p = 168,68^{***} \ln \rho_b - 55,49^{***} \psi m - 90,94$	0,868***
Parafield[3]	$q_p = 104,04^{**} \ln \rho_b - 29,17^{**} \psi m - 43,58$	0,969**

q_p = Soil strength, bar
ρ_b = Bulk density, g cm^{-3}
ψm = Matric potential, bar
b_1 and b_2 = Partial regression coefficients

[+]Data from sources shown:

[1]Taylor *et al.* (1966)
[2]Taylor (1974)
[3]Barley *et al.* (1965)

5.3 Data from undisturbed cores

The undisturbed cores taken from the tillage trials gave a unique opportunity for evaluating the combined effect of bulk density, soil texture and soil moisture on soil strength. In an initial plot of soil strength against bulk density at a particular matric potential, it soon became obvious that the relationship was also dependent upon soil texture. In order to establish the relationship between soil strength, bulk density and silt plus clay content, multiple regression models were set up in which several different functions were tested. The best general fit was found to be:

$$\ln q_p = b_1 \ln \rho_b + b_2 \ln(\text{silt} + \text{clay}) + c \qquad 5.2$$

where q_p = soil strength (bar); ρ_b = bulk density (g cm^{-3}); (silt + clay) = silt plus clay content %, and b_1 and b_2 are the partial regression coefficients. This model was then fitted for the data obtained on cores from Domboshawa, Grasslands and Makoholi at -100 and -1 000 mbar matric potential, and from Hatcliffe at -200 and -1 000 mbar matric potential. R^2 values and the significance of the overall regressions and partial regression coefficients were calculated.

The calculated regression equations for the relationship between soil strength, bulk density and silt plus clay content are presented in Table 5.2. In every case the overall regression was very highly significant (P = 0,001). The regression of soil strength on bulk density, independent of silt plus clay content was also very highly significant at all four sites. The regression of soil strength on silt plus clay content, independent of bulk density was very highly significant at Domboshawa, Grasslands and Hatcliffe, but not at Makoholi. The high R^2 values show that much of the variability in soil strength at a particular matric potential is attributable to variations in bulk density and silt plus clay content. Figure 5.1 shows response surfaces plotted for the four sites at each of the two matric potentials.

Data on disturbed soils (section 5.2) showed that soil moisture had a very highly significant effect on soil strength. In order to establish the effect of soil moisture on soil strength in the undisturbed soils, the significance of the difference in soil strength at 'field capacity' (-100 mbar at Domboshawa, Grasslands and Makoholi, and -200 mbar at Hatcliffe) and -1 000 mbar matric potential was tested statistically, using the Student's t-test for paired data (Rayner, 1969). The differences were all very highly significant (P = 0,001). In the coarse-textured soils the percentage increase in soil strength on drying from -100 to -1 000 mbar was between 62 and 71%, and at Hatcliffe (fine-textured soil) the increase on drying from -200 to -1 000 mbar was 39%.

TABLE 5.2

Calculated multiple regression functions and significance levels for the relation:

$$\ln q_p = b_1 \ln \rho_b + b_2 \ln(\text{silt} + \text{clay}) + c$$

at each of two matric potentials for the four tillage trial soils

Soil	Calculated regression function	R^2
Domboshawa:		
-100 mbar	$\ln q_p = 7{,}36^{***} \ln \rho_b + 1{,}04^{***} \ln(s+c) - 3{,}48$	$0{,}855^{***}$
-1 000 mbar	$\ln q_p = 7{,}04^{***} \ln \rho_b + 1{,}01^{***} \ln(s+c) - 2{,}69$	$0{,}830^{***}$
Grasslands:		
-100 mbar	$\ln q_p = 7{,}06^{***} \ln \rho_b + 0{,}83^{***} \ln(s+c) - 2{,}40$	$0{,}863^{***}$
-1 000 mbar	$\ln q_p = 7{,}94^{***} \ln \rho_b + 1{,}13^{***} \ln(s+c) - 3{,}07$	$0{,}841^{***}$
Makoholi:		
-100 mbar	$\ln q_p = 9{,}66^{***} \ln \rho_b - 0{,}10^{(NS)} \ln(s+c) - 1{,}75$	$0{,}645^{***}$
-1 000 mbar	$\ln q_p = 10{,}47^{***} \ln \rho_b - 0{,}12^{(NS)} \ln(s+c) - 1{,}66$	$0{,}517^{***}$
Hatcliffe:		
-200 mbar	$\ln q_p = 4{,}33^{***} \ln \rho_b + 1{,}68^{***} \ln(s+c) - 4{,}61$	$0{,}745^{***}$
-1 000 mbar	$\ln q_p = 4{,}33^{***} \ln \rho_b + 1{,}37^{***} \ln(s+c) - 3{,}13$	$0{,}769^{***}$

q_p = Soil strength, bar

ρ_b = Bulk density, g cm^{-3}

$(s+c)$ = Silt + clay, %

b_1 and b_2 = Partial regression coefficients

5.4 Discussion

The relationships between soil physical factors and soil strength have been studied in a wide range of soil types on both disturbed and undisturbed samples. Bulk density, matric potential and soil texture have all been shown to have a significant effect on soil strength. Two main factors affecting resistance to penetration (soil strength) are frictional forces at interparticle contact surfaces, and cohesive

Regression: $\ln q_p = 7,36^{***} \ln \rho_b + 1,04^{***} \ln(S+c) - 3,48$

$R^2 = 0,855^{***}$

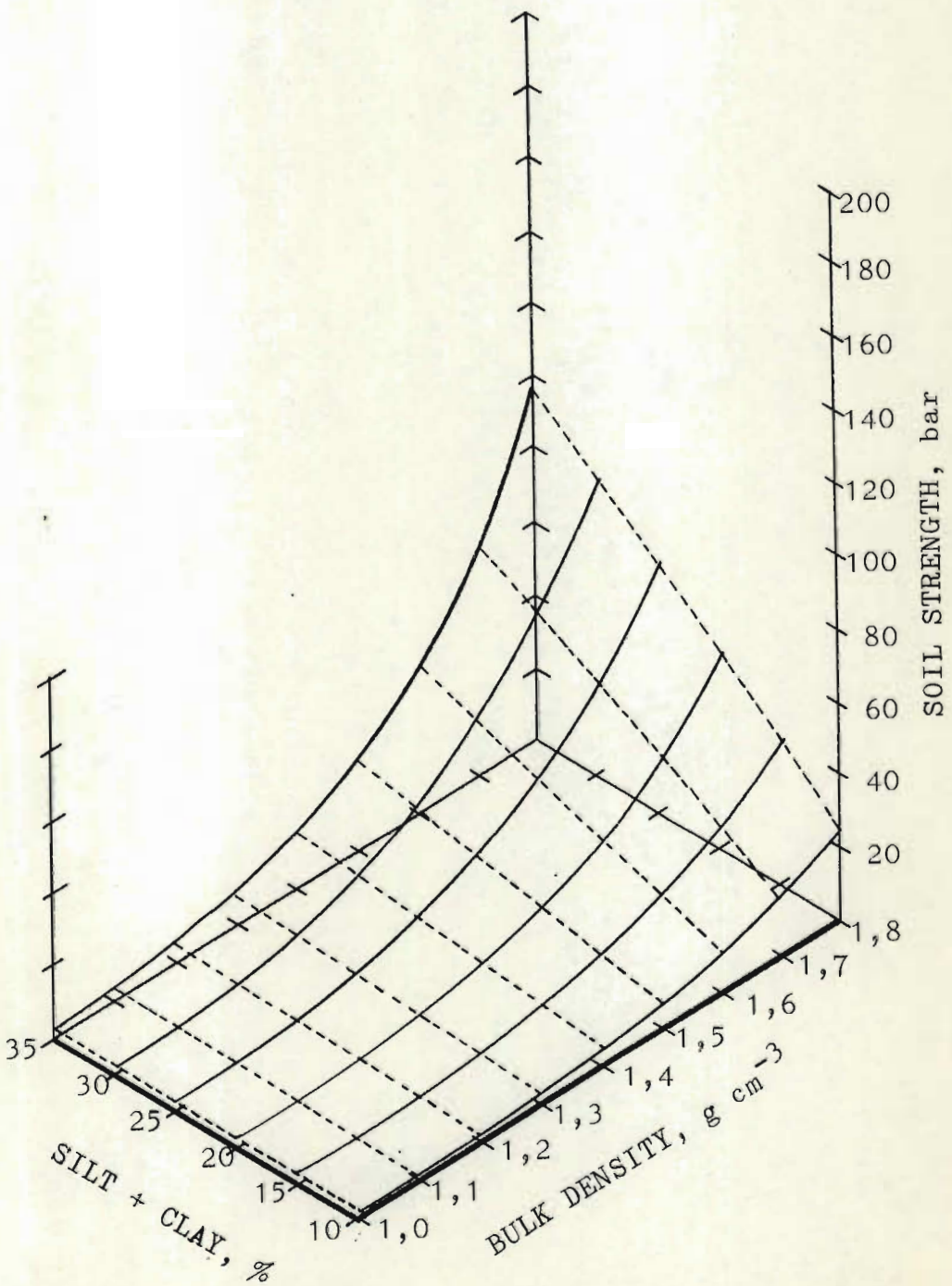

Fig. 5.1 Calculated response surfaces showing soil strengt as a function of bulk density and silt plus clay content:
(a) DOMBOSHAWA soil at -100 mbar matric potentia

Regression: $\ln q_p = 7,^{***}04 \ln \rho_b + 1,^{***}01 \ln(S+c) - 2,69$

$R^2 = 0,830^{***}$

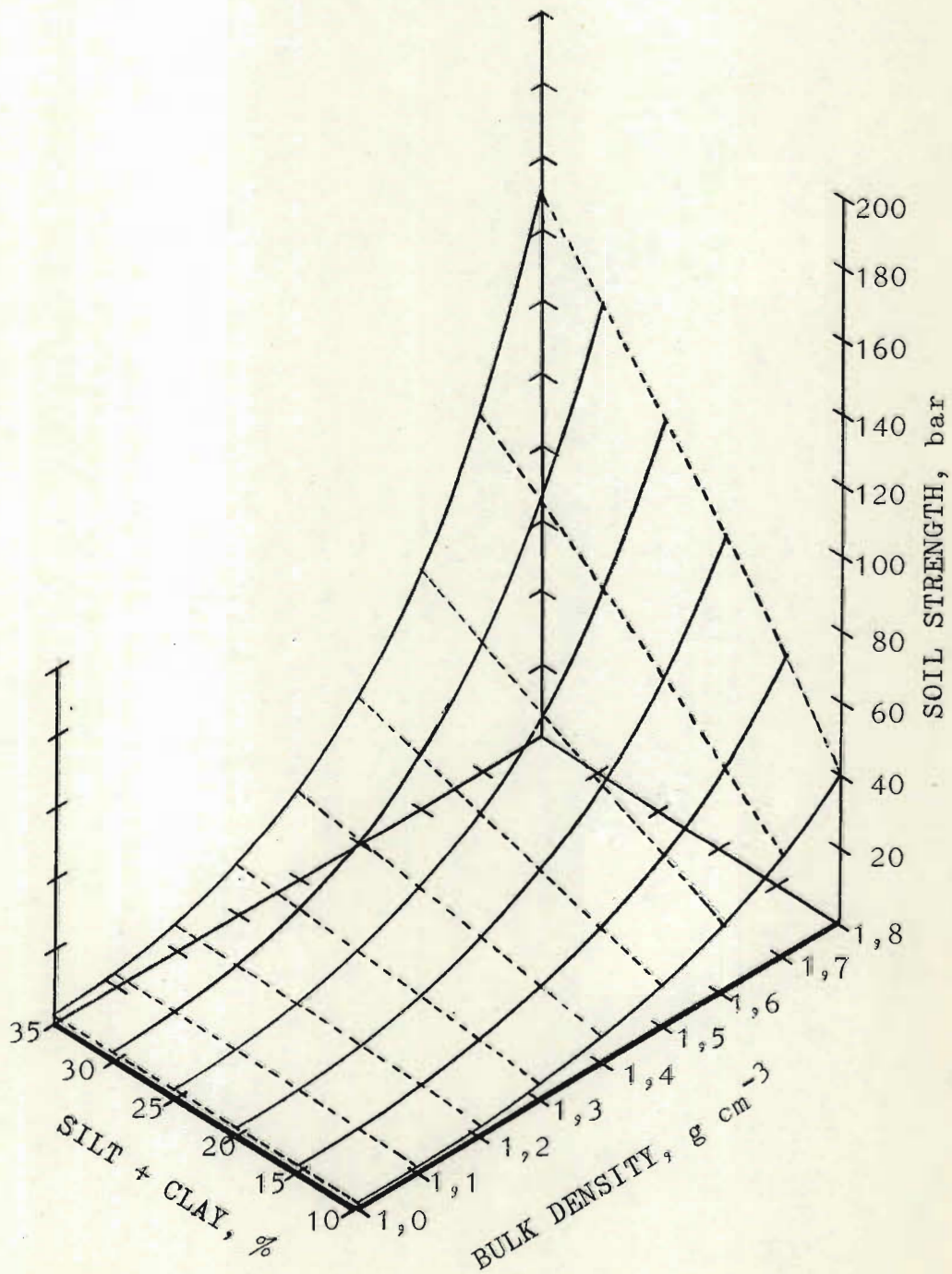

Fig. 5.1(b) DOMBOSHAWA soil at -1 000 mbar matric potential

Regression: $\ln q_p = 7,06^{***} \ln \rho_b + 0,83^{***} \ln(S+c) - 2,40$

$R^2 = 0,863^{***}$

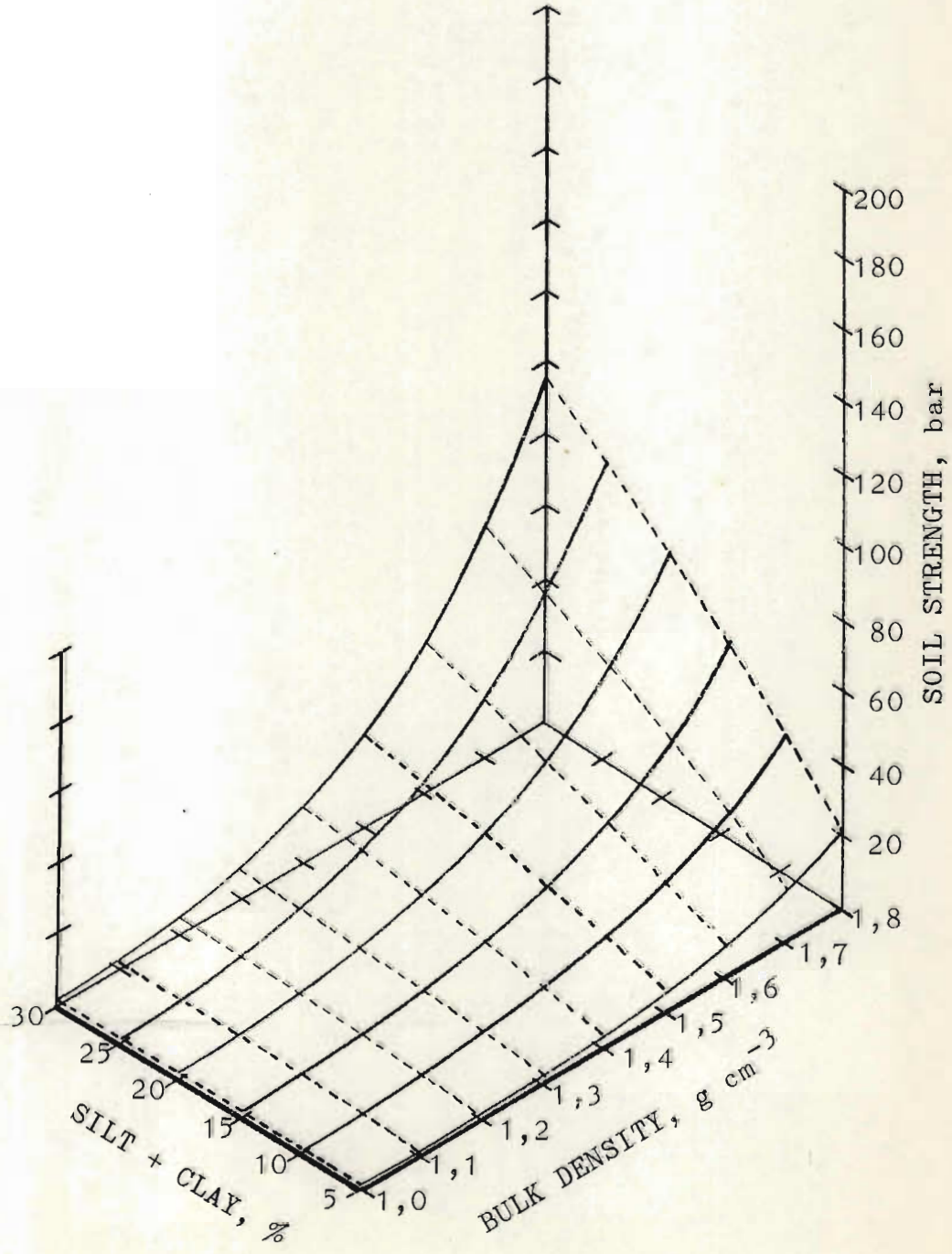

Fig. 5.1(c) GRASSLANDS soil at -100 mbar matric potentia

Regression: $\ln q_p = 7,^{***}94 \ln \rho_b + 1,^{***}13 \ln(S+c) - 3,07$

$R^2 = 0,841^{***}$

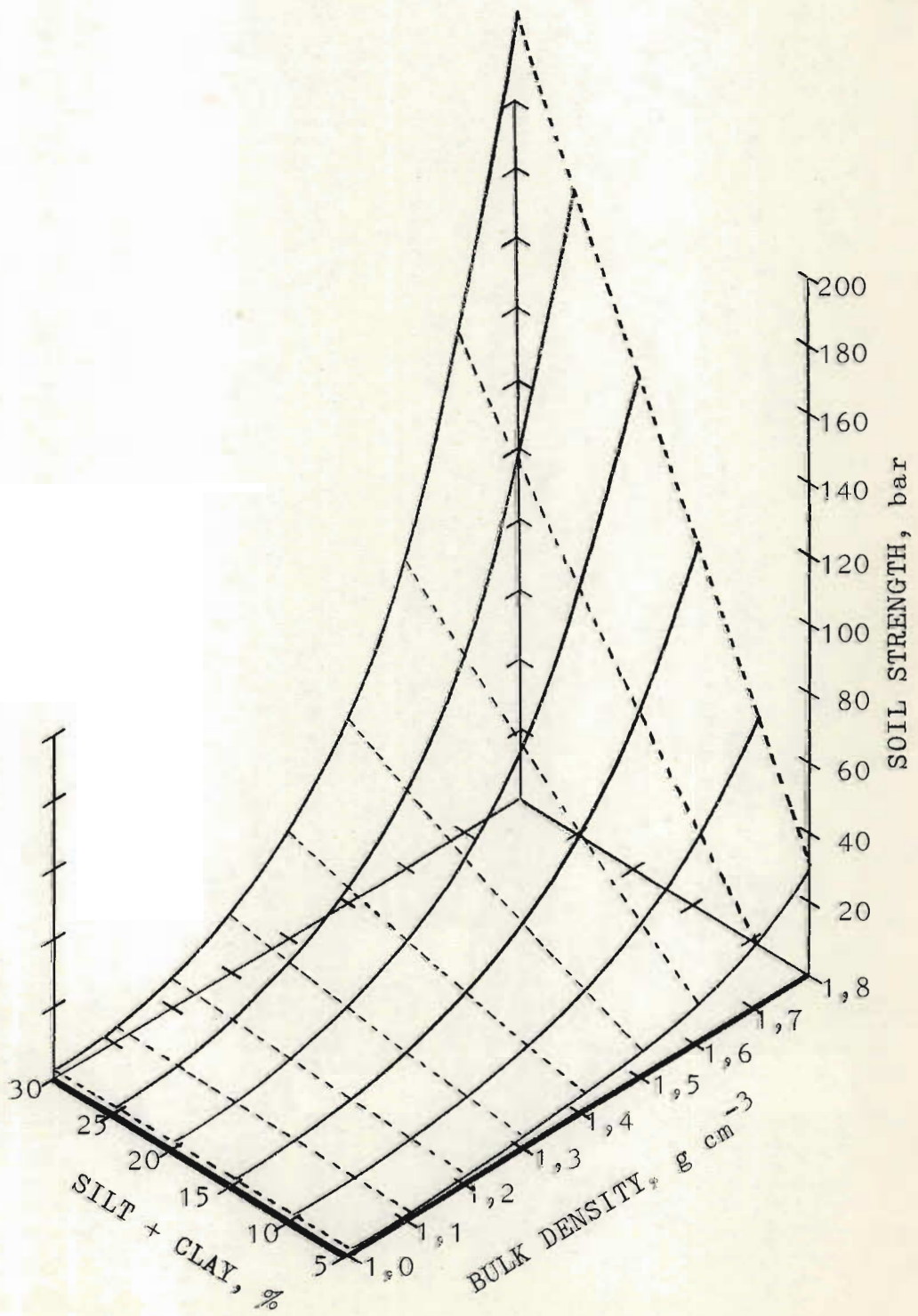

Fig. 5.1(d) GRASSLANDS soil at -1 000 mbar matric potential

Regression: $\ln q_p = 9{,}66^{***} \ln \rho_b - 0{,}10^{(NS)} \ln(S+c) - 1{,}75$

$R^2 = 0{,}645^{***}$

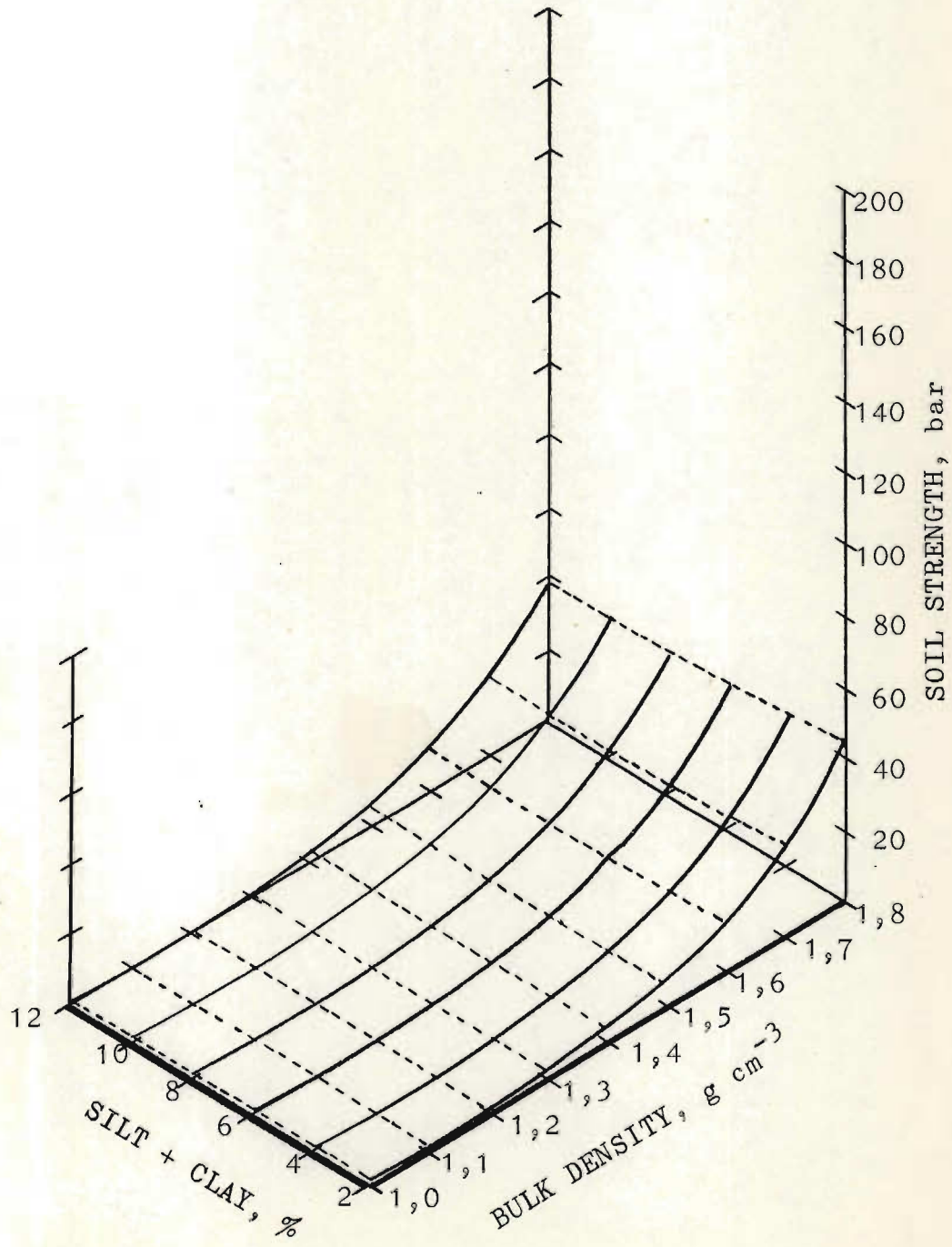

Fig. 5.1(e) MAKOHOLI soil at -100 mbar matric potential

Regression: $\ln q_p = 10{,}47^{***} \ln \rho_b - 0{,}12^{(NS)} \ln(S+c) - 1{,}66$

$R^2 = 0{,}517^{***}$

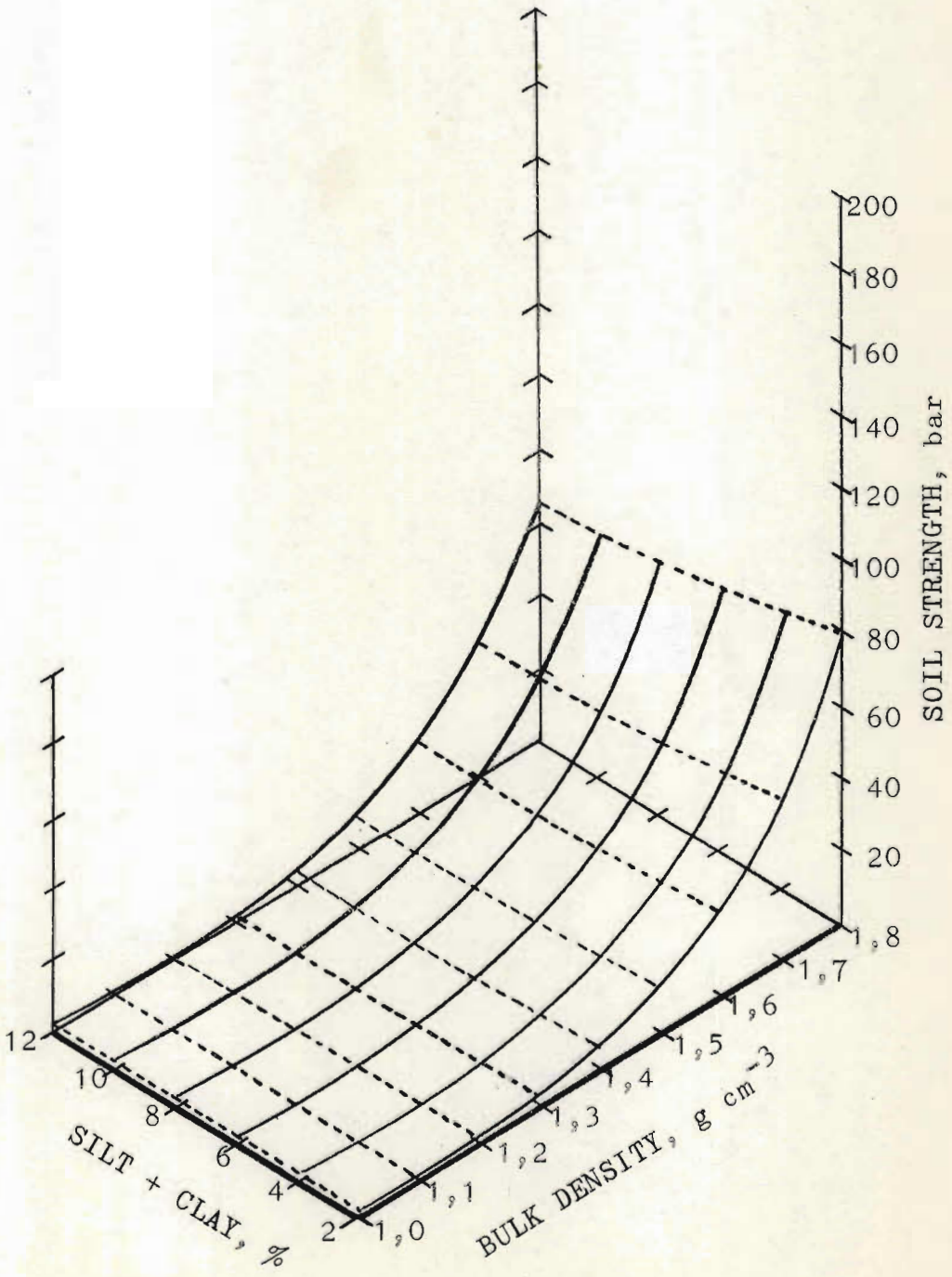

Fig. 5.1(f) MAKOHOLI soil at -1 000 mbar matric potential

Regression: $\ln q_p = 4,33^{***} \ln \rho_b + 1,68^{***} \ln(S+c) - 4,61$

$R^2 = 0,745^{***}$

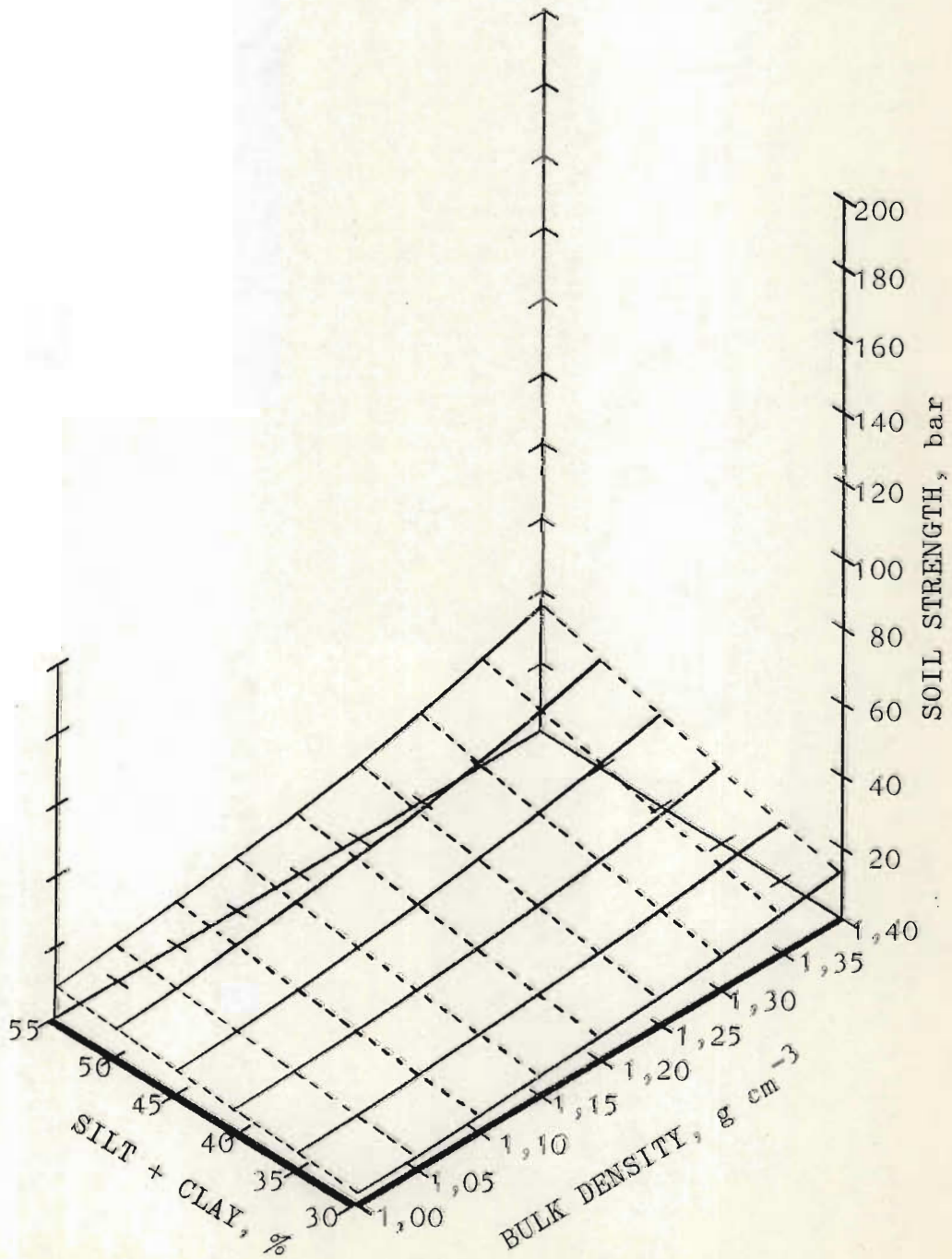

Fig. 5.1(g) HATCLIFFE soil at -200 mbar matric potential.

Regression: $\ln q_p = 4,^{***}33 \ln \rho_b + 1,^{***}37 \ln(S+c) - 3,13$

$R^2 = 0,769^{***}$

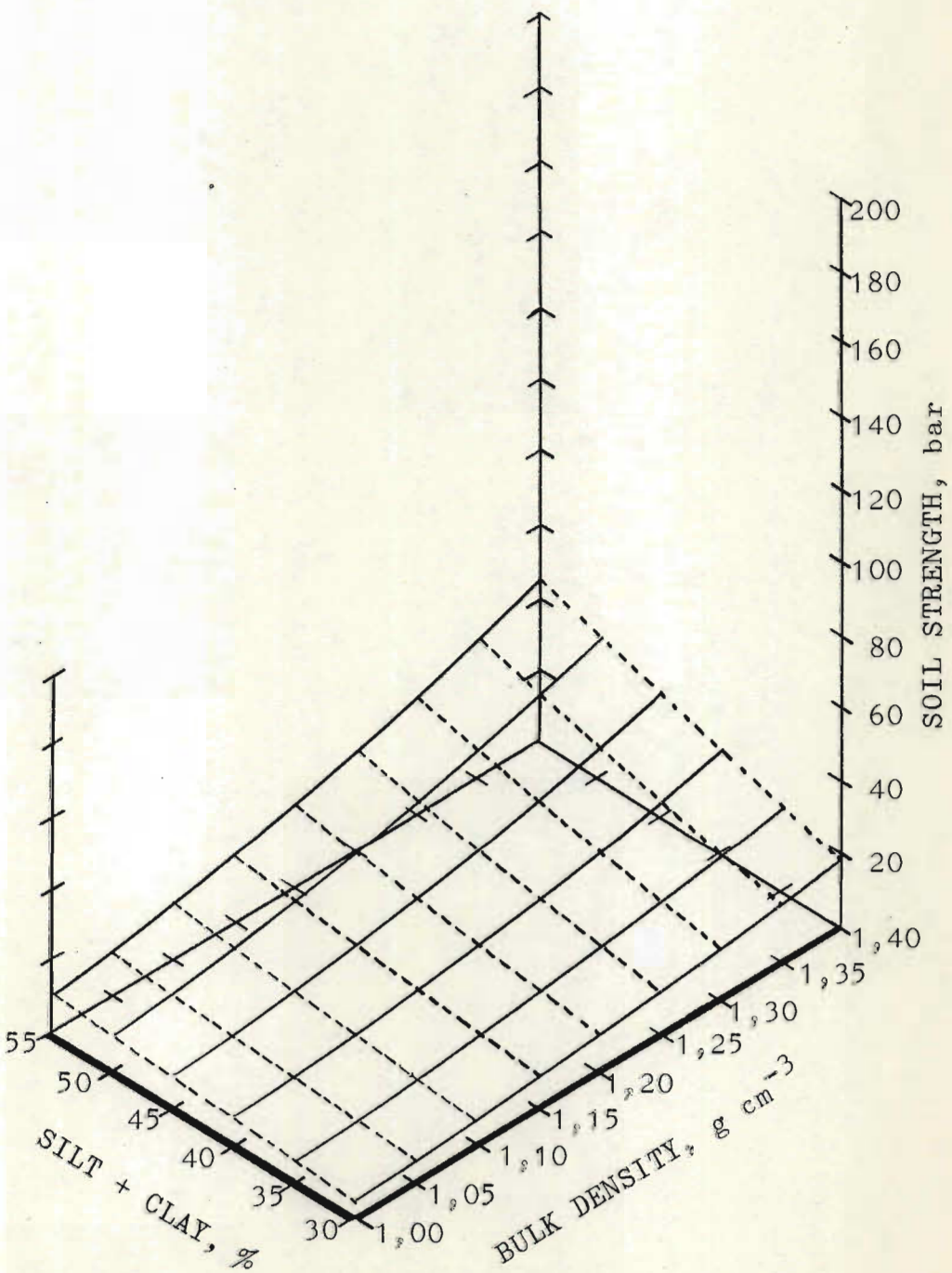

Fig. 5.1(h) HATCLIFFE soil at -1 000 mbar matric potential

forces between particles. Frictional forces are mainly physical and depend upon the frictional properties of the soil material and the extent and condition of the interparticle contacts. Cohesive forces are physicochemical in origin, and depend mainly on cementation (organic matter, iron and aluminium oxides etc.) and the strength of moisture bonds between particles. Bulk density, matric potential and soil texture influence soil strength by influencing these frictional and cohesive forces.

Data from undisturbed cores show that silt plus clay content has a highly significant effect on soil strength at Domboshawa, Grasslands and Hatcliffe, but not at Makoholi. At Makoholi silt plus clay content is very low ($\lesssim 7\%$). This produces a 'rigid' system in which frictional forces are high. This latter fact is also evidenced by the high partial regression coefficient of soil strength on bulk density independent of silt plus clay content at Makoholi, where an increase in bulk density produces a relatively greater increase in soil strength than it does at Hatcliffe.

Cohesive forces in the soil are determined by the strength of moisture bonds holding particles together as well as by cementing materials. Mirreh and Ketcheson (1972), whilst not discounting the contribution of cementing agents to cohesive forces in soils, regard them as playing a relatively minor role compared to the contribution of interparticle moisture bonds. The contribution of these moisture bonds is a function of soil matric potential, pore-size distribution, and the degree to which various sized pores are drained. With decreasing matric potential, interparticle bonds increase in strength as water is drained from the larger pores, and pores with smaller moisture surface curvature radii become functional in water retention (Gardner, 1961). Thus the influence of matric potential on soil strength can be regarded as being related to the moisture retention properties of the soil (Williams and Shaykewich, 1970).

This latter point is illustrated by data obtained for the undisturbed cores studied in this investigation. At Hatcliffe,

the soil is fine-textured, so a relatively small amount of water is withdrawn between 'field capacity' and -1 000 mbar matric potential, and soil strength increases by about 39% on drying. At the other three sites, more water is extracted between the two moisture levels, and soil strength increases by about 67%.

5.5 Summary

The relationships between soil physical factors and soil strength have been studied in a wide range of soil types on both disturbed and undisturbed soils. Data presented show that soil strength increases:

a) with increase in bulk density,
b) with decrease in matric potential, and
c) with increase in silt plus clay content.

CHAPTER 6

SOIL PHYSICAL CONDITIONS: ROOT GROWTH AND MAIZE YIELD

6.1 Introduction

The suitability of soil as an environment for root growth and function depends on the availability of water, nutrients and oxygen, on temperature, and on the degree of mechanical impedance to root extension. These factors, in turn, affect the total amount of root, and its capacity to absorb water, nutrients and oxygen.

Under field conditions the soil is continuously subjected to external and internal forces which tend to change its total volume. These changes arise as a consequence of rainfall, traffic or tillage, and from swelling and shrinkage of the constituents within the soil. As soil is compressed its pore volume decreases, its bulk density increases and there is a decrease in the proportion of large pores.

Physical factors most likely to affect root growth in the soils studied in this investigation, viz. soil strength, bulk density, air space and available moisture have been measured. Layers with high soil strength have been shown to be present below the plough layer in all the treatments. Before considering the effect of these high soil strength pans on root growth it is perhaps pertinent to examine the characteristics of soil pans and how they develop.

6.2 Characteristics of pans

Two different types of soil pans are defined (Anonymous, 1965). These are:

a) Genetic pans. Natural subsurface soil layers of low or very low permeability with a high concentration of small particles, and differing in certain physical and chemical properties from the soil immediately above or below the

pan. Genetic pans include claypans, fragipans and hardpans.

b) Pressure or induced pans. Subsurface horizons or soil layers having a higher bulk density and a lower total porosity than the soil directly above or below, formed as a result of pressure that has been applied by normal tillage operations or by other artificial means. They are frequently referred to as ploughpans, ploughsoles or traffic pans.

Taylor, Mathers and Lotspeich (1964b) studied 17 root restricting pans in the Southern Great Plains of America in an effort to determine firstly, the soil characteristics associated with these root-restricting pans, and secondly, the reason or reasons that root-restricting pans occur.

They found little evidence of the pans fitting the definition for genetic pans because they failed to meet the requirements of low permeability, and particle size and chemical properties within the pan did not differ appreciably from those in the soil immediately above and below the pan. Neither did the pans meet the definition for pressure pans, because the definition implies that the pans have been formed by artificial means. The pans they studied did, however, possess certain attributes in common with those defined as pressure pans, viz.

a) all of the pans were formed near cleavage planes caused by tillage,

b) there were no consistent differences in chemical or mineralogical properties between the pans and the layers immediately above and below them, and

c) bulk density of the pan was greater than that of the ploughed layer in most cases, but was not always greater than that in the soil below.

The pans studied in this investigation showed many of the characteristics of the pans studied by Taylor *et al.* (1964b) viz.

a) with the exception of the 100 mm ploughing depth treatment at Hatcliffe, all the pans were formed just below the nominal ploughing depth,

b) there were no apparent consistent differences in chemical or mineralogical properties between the pans and the layers immediately above and below them. Thompson (1965) describes profiles similar to those of the tillage trials - there was no evidence of genetic pans occurring in these soils, and

c) bulk density of the pan was greater than that of the ploughed layer in most cases, but was not always greater than in the soil below. This latter point is illustrated by reference to the bulk density/depth profiles presented in Fig. 6.1 for each of the three ploughing depth treatments at the four trial sites. Bulk densities were calculated from field and laboratory measurements obtained from the trials.

Taylor et al. (1964b) concluded that the pans they studied were neither wholly genetic nor wholly pressure-induced in origin They believed that it was excessive soil strength, which develope largely as a result of drought conditions that caused the root-restricting features of these layers to appear. When a tillage pan as defined was present, this aided the development of excessive strength.

In order to demonstrate the effect of drying on soil strengt within the tillage trial soils, soil strengths at -1 000 mbar were calculated using the field and laboratory data obtained in this investigation. Soil strength/depth profiles at 'field capacity' and -1 000 mbar matric potential for each of the ploughing depth treatments at the four trial sites are presented in Fig. 6.2. These show that while soil strengths within the hard layers at 'field capacity' were between 16 and 24 bars, these increased to between 25 and 39 bars on drying to -1 000 mbar. The effects of soil strengths of this order on root growth will be discussed in section 6.5.

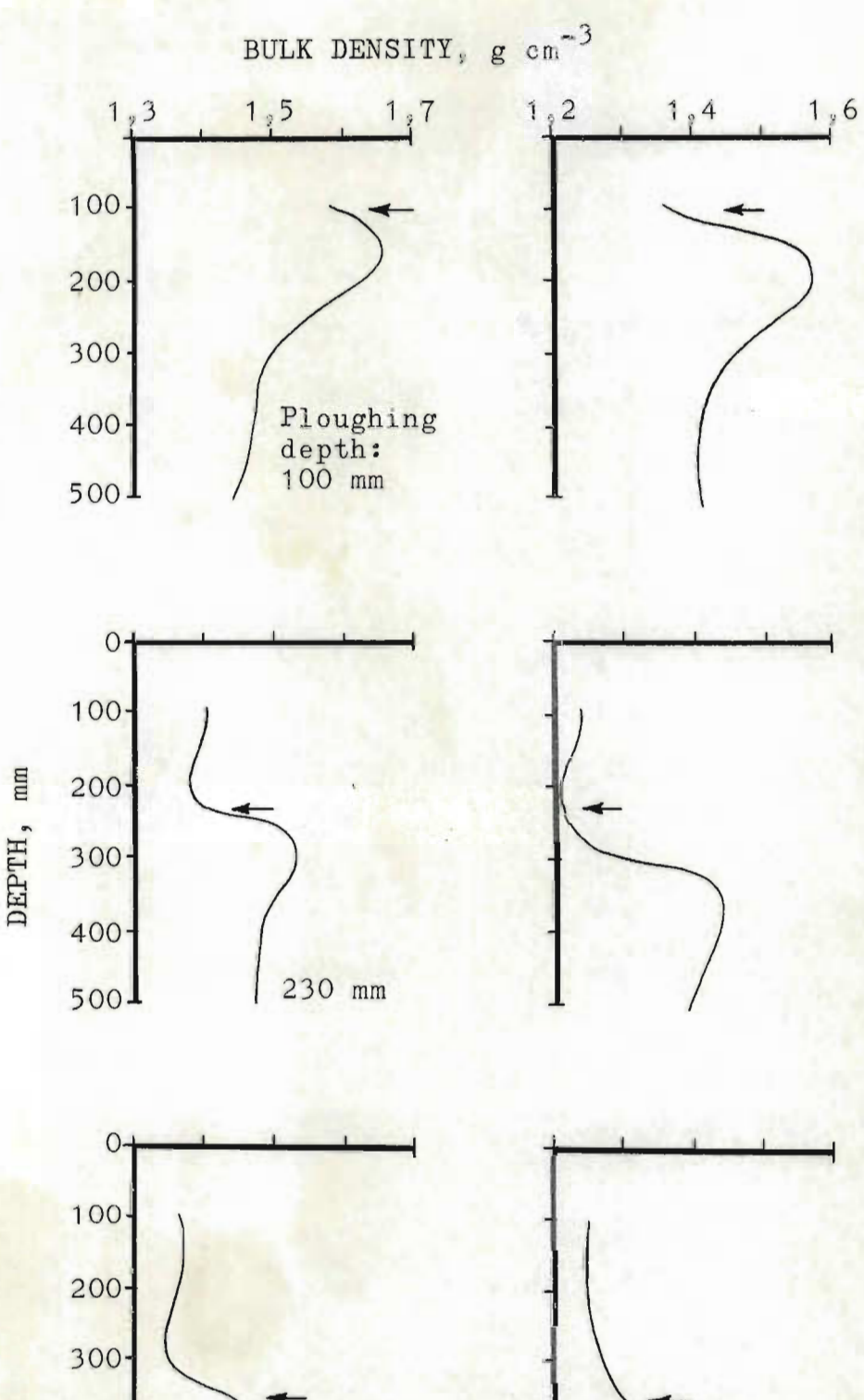

Fig. 6.1 Bulk density/depth profiles calculated from fiel and laboratory data (the arrows indicate depth o ploughing)

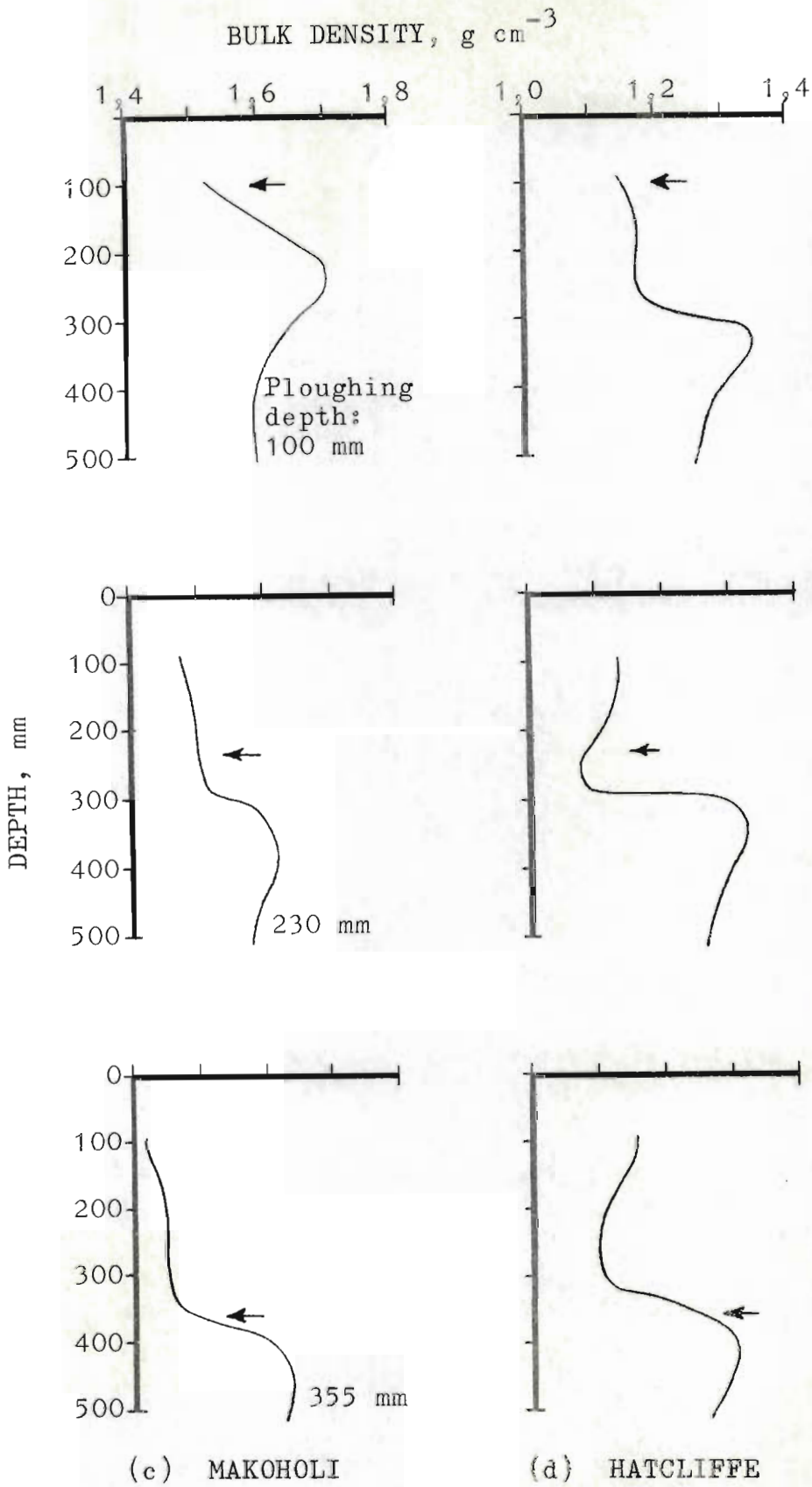

Fig. 6.1(continued) Bulk density/depth profiles calculated from field and laboratory data (the arrows indica depth of ploughing)

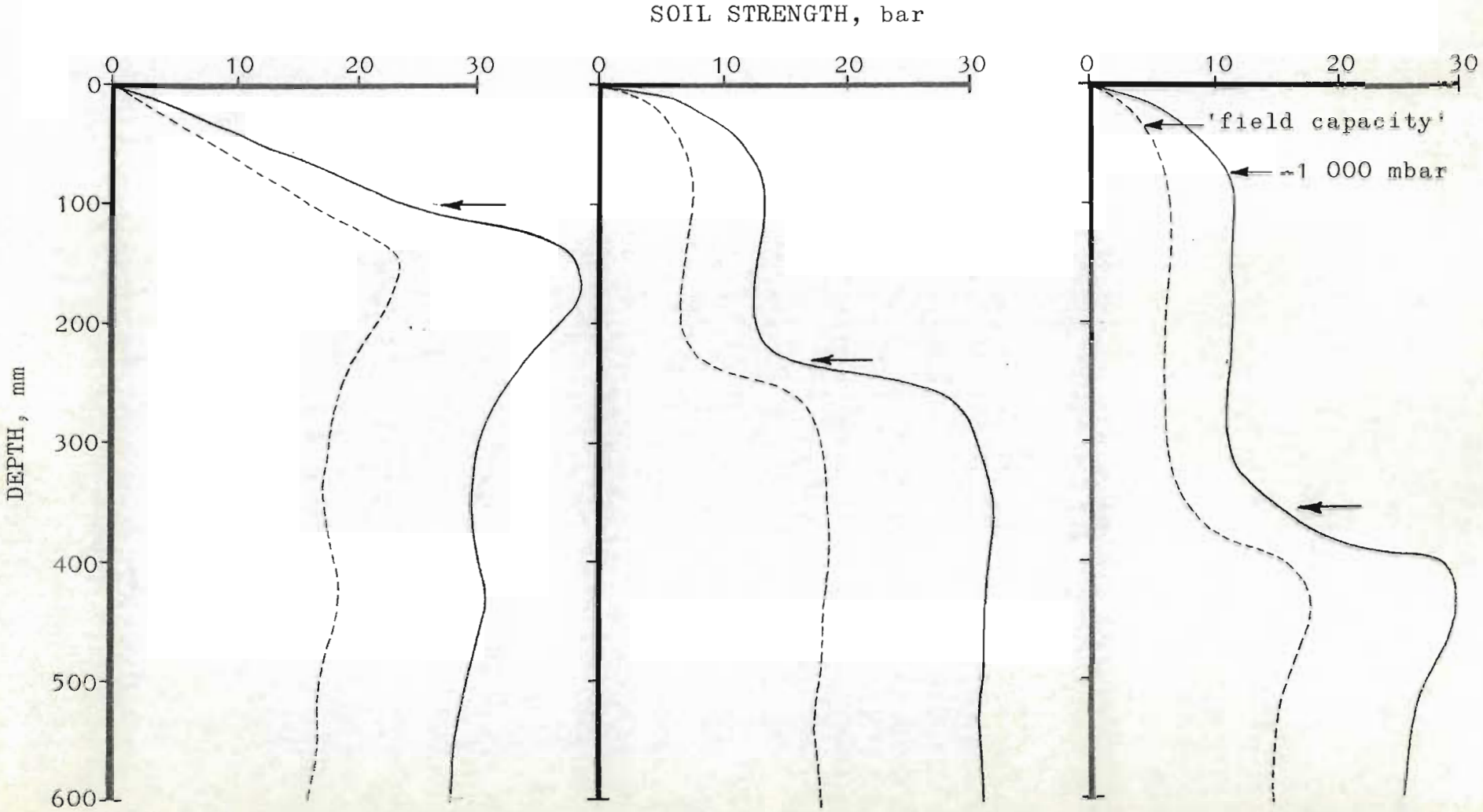

Fig. 6.2(a) Soil strength/depth profiles at 'field capacity' and -1 000 mbar at DOMBOSHAWA (-1 000 mbar profiles calculated from field and laboratory data)

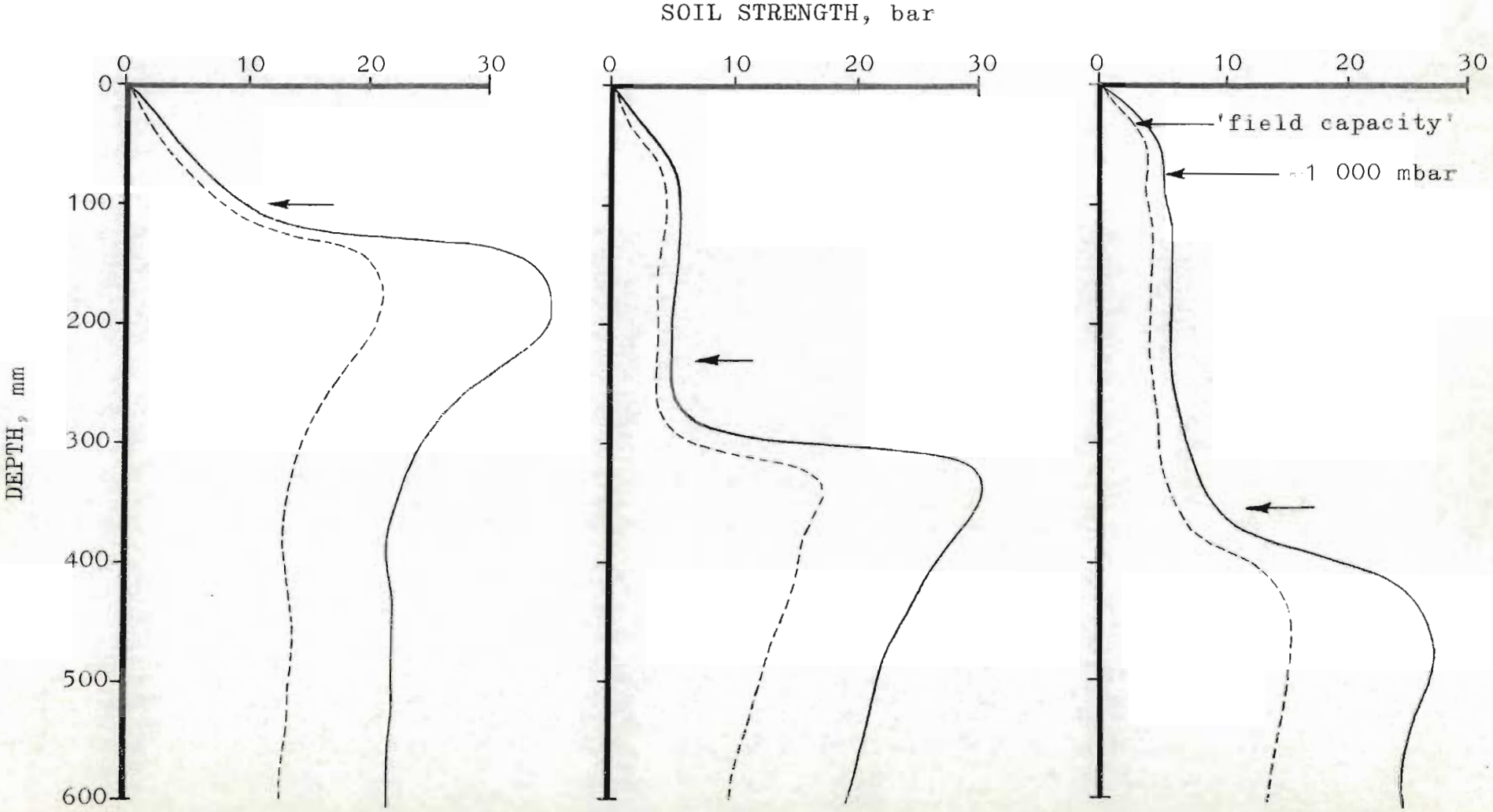

Fig. 6.2(b) Soil strength/depth profiles at 'field capacity' and -1 000 mbar at GRASSLANDS (-1 000 mbar profiles calculated from field and laboratory data)

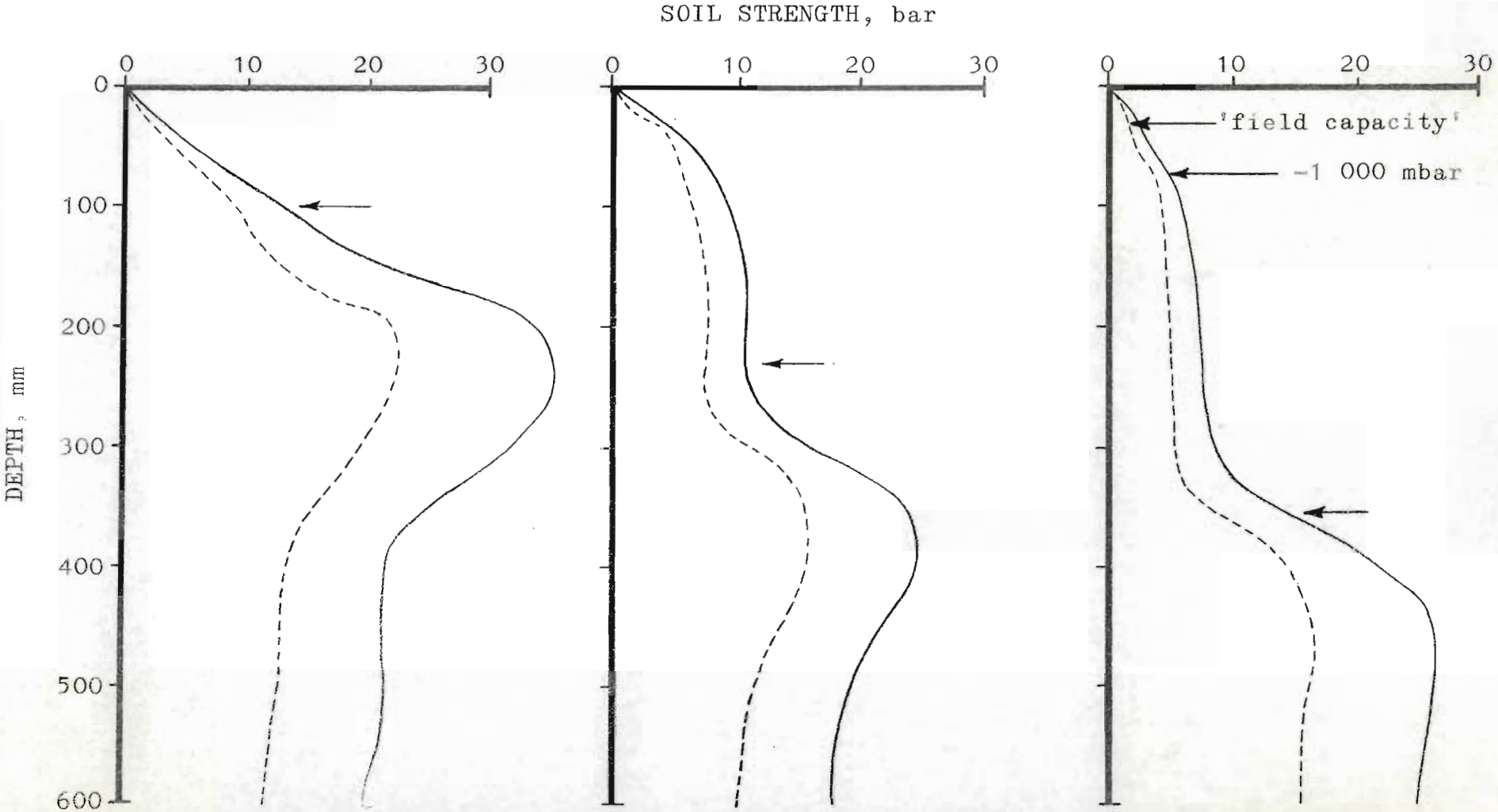

Fig. 6.2(c) Soil strength/depth profiles at 'field capacity' and -1 000 mbar at MAKOHOLI (-1 000 mbar profiles calculated from field and laboratory data)

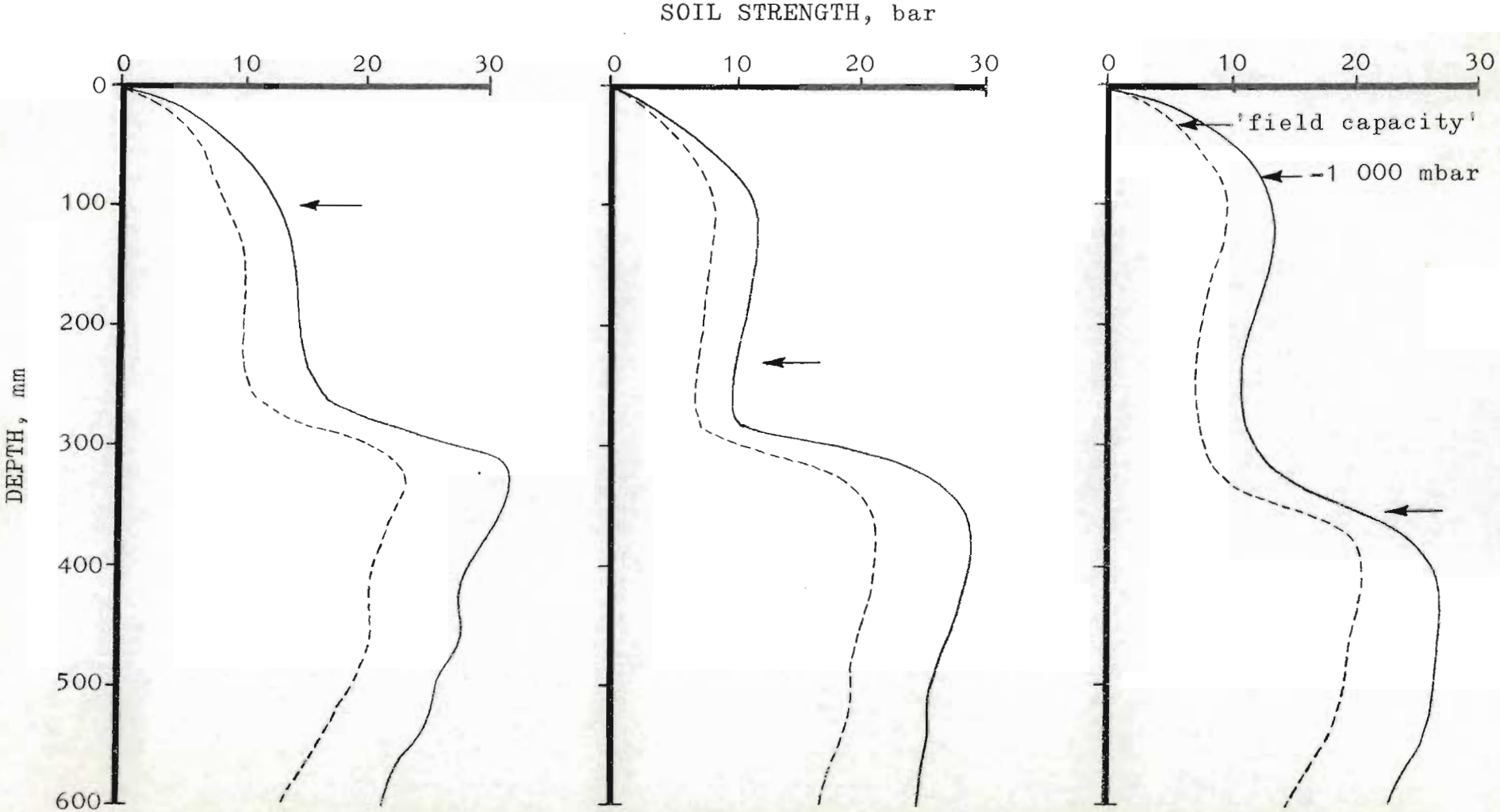

Fig. 6.2(d) Soil strength/depth profiles at 'field capacity' and -1 000 mbar at HATCLIFFE (-1 000 mbar profiles calculated from field and laboratory data)

6.3 Development of pans

Bulk density changes within soils arise as a result of internal and external forces tending to change the total volume of the soil. These forces are:

a) Traffic and tillage. Any externally applied force will tend to change soil density, the change in density being a function of both the compactive pressure and the moisture content. Thus in a disc-ploughing operation the soil will be subjected to the pressure of the tractor wheels and also to shearing and compression at the leading edge of the plough disc. The effect of these two factors on soil density will depend upon the moisture content of the soil at the time of ploughing.

b) Rainfall. The impact of rainfall on exposed soil causes aggregates to disperse, these dispersed particles being carried downwards into the soil pores, causing increased compaction and decreased pore space. The influence of rainfall is confined to a narrow surface layer.

c) Shrinkage and swelling. Gerard, Bloodworth, Burleson and Cowley (1961) reported on the development of hardpans under laboratory conditions. They found that although the laboratory hardpans were not of the same intensity as field hardpans, they were characteristically similar. They postulated that the factors contributing to the development of hardpans in the laboratory were:

   i) cohesive forces of the water molecules,
   ii) rate of soil moisture loss,
   iii) size distribution of soil particles, and
   iv) the overall wetting and drying cycles.

In subsequent work Gerard *et al.* (1962), Gerard (1965) and Gerard, Cowley and Kunze (1966) studied the effect on hardpan development of the rate of moisture loss, and of cyclic wetting and drying.

Considering firstly the effect of rate of drying on soil strength, Gerard et al. (1966) used the modulus of rupture technique of Richards (1953) to measure strengths of briquettes of three artificial soils dried quickly (50C) and slowly (27C, relative humidity 80%). Soil strengths were between 48 and 70% higher in the briquettes which were dried slowly.

The reason given for the increased soil strength on slow drying was that during slow drying the cohesive action of water molecules drew particles together, resulting in close-packing of particles, and consequently more interparticle bonds. Fast drying, on the other hand, produced briquettes of lower strength due to the disruptive action of rapidly escaping water molecules on the arrangement of soil particles. Photomicrographs taken of the soil fabric under the two drying conditions confirmed that close-packing took place under the slow drying conditions.

The influence of cyclic wetting and drying on soil strength was studied by Gerard et al. (1962). They found that soil strength in a fine sandy loam subjected to three wetting and drying cycles increased by up to 43% when subjected to a further six wetting and drying cycles. This too they attributed to close-packing of particles. They also found that the rate of particle rearrangement on wetting and drying was quite fast.

Gerard et al. (1962) regarded the arrangement of the soil mass (close-packing of particles) as being dependent upon climate, type of crop, and management practices.

6.4 Pans in the tillage trials

The existence of pans in the tillage trials has been shown conclusively in both field and laboratory measurements. Most of these pans possess attributes in common with tillage pans, but have not necessarily developed exclusively through the effects of the tillage treatments imposed during the course of the tillage trials. More likely though, they have developed

as a result of interactions between the previous history of the trials, imposed tillage treatments, climatic and crop factors.

The effects of some of these factors on pan development are illustrated in data obtained by Wilson (Branch of Chemistry and Soil Science, Ann. Report, 1968-69) and presented in Fig. 6.3. This shows soil strength/depth profiles obtained on Grasslands at 'field capacity' in virgin woodland, in grass eight years after being ploughed, and within the tillage trial on the 100 mm ploughing depth treatment. Under grass there was a well-defined pan beginning at about 50 mm below the soil surface. Wilson stated that this was probably due to severe puddling of the soil under wet conditions. Under the 100 mm ploughing depth treatment the pan was quite similar to that under grass, but began at a depth of about 100 mm.

The Grasslands tillage trial had been under grass ley for several years, and was uniformly ploughed to 100 mm prior to the imposition of the tillage treatments. On the evidence of Wilson it appears that a pan was already present near the surface at the commencement of the trial, but apart from a relatively soft pan at about 350-400 mm there was no evidence of pans occurring below about 300 mm. Thus the pans occurring on the 230 and 355 mm ploughing depth treatments developed during the course of the trial, while the pan on the 100 mm ploughing depth treatment was probably already present at the commencement of the trial.

Although no evidence is available on the soil strength/depth conditions pertaining at Makoholi prior to the institution of the tillage trial there, the previous history of the site is similar to that at Grasslands. The site was uniformly ploughed to 100 mm after being under grass fallow for several years.

At Domboshawa the trial site had been under maize and was ploughed to 300 mm before the start of the tillage trial. This would have broken up any pans present within the top 300 mm of soil. The pan on the 100 mm ploughing depth

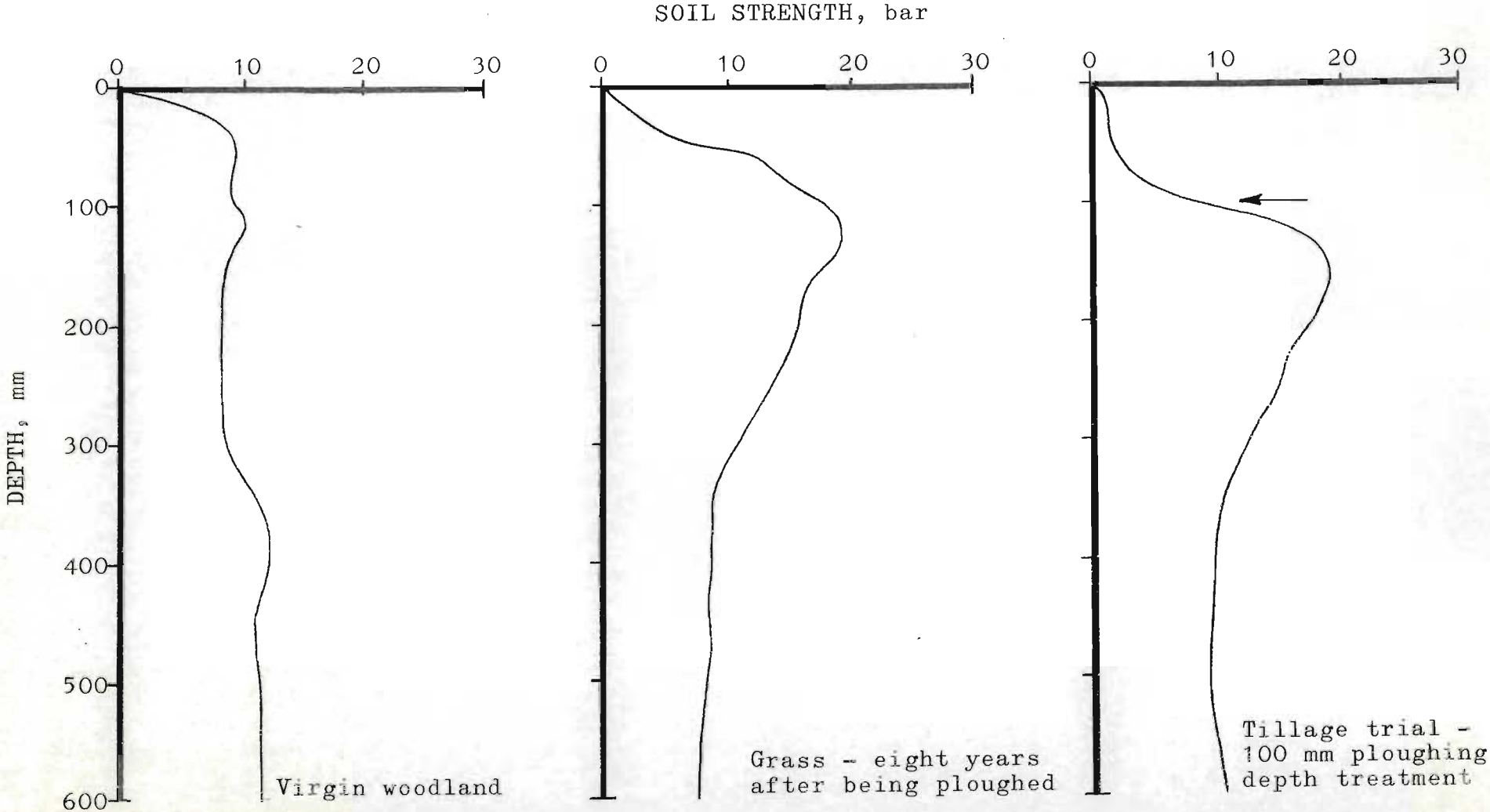

Fig. 6.3 Soil strength/depth profiles obtained at 'field capacity' on three different sites at Grasslands by Wilson

treatment was wholly contained within the top 300 mm, so it can be concluded that this pan has developed primarily as a result of ploughing continuously to 100 mm.

The Hatcliffe trial had been under maize for several years, ploughed regularly to 300 mm. The pans occurring at depth in these profiles were therefore probably already present at the commencement of the trial. A major difference between the soil strength/depth profile in the 100 mm ploughing depth treatment at Hatcliffe and those at the other three sites was the absence just below the nominal depth of ploughing of a hard layer. The clay fraction of the granite-derived soils (Domboshawa, Grasslands and Makoholi) consists mainly of kaolinite and free sesquioxides of iron and aluminium while at Hatcliffe, though kaolinite predominates, illite-montmorillonoid mixed layer minerals also occur. These latter minerals impart to the Hatcliffe soil a fairly marked shrink-swell characteristic. This was evidenced by cracks observed in the dry field soil, and by shrinkage of the undisturbed soils on drying - the cores shrank by approximately 10% between 'field capacity' and oven dryness. The effect of this cracking, which is mainly in the upper layers of the soil due to the more intense drying, is one of 'self-ploughing' and this breaks up pans which otherwise might have formed in the surface layers. Taylor and Bruce (1968) made a similar observation in finding that the likelihood of crop yield reduction due to high soil strength was reduced in cracking clays.

In summary, therefore, it has been shown that pans exist in all the tillage trial soils. In all the profiles studied, the pans exhibit many of the characteristics of tillage pans, but their existence cannot be attributed exclusively to the ploughing depth treatments imposed in the tillage trials. Rather, the pans have resulted from a combination of interacting factors, viz. previous history of the soils, the imposed tillage treatments, crop and climatic factors.

The effects of soil strength on root growth will now be considered.

6.5 Effect of soil strength on root growth

Soil resistance to the penetration of a probe, termed soil strength has been widely used as an index of soil resistance to root growth. That this is a more useful index to relate to root growth than is bulk density was shown by Taylor and Gardner (1963). These authors obtained a very highly significant linear correlation (R^2 = 0,92) between root penetration and soil strength. The correlation with bulk density was not as close (R^2 = 0,35). This finding was further confirmed by Taylor and Burnett (1964) who stated that it was soil strength and not any other soil physical factor which actually controlled penetration of cotton taproots in the moist soil they were studying.

6.5.1 Data from the literature

In order to evaluate the relationship between root growth and soil strength, data from the literature were studied. Root growth parameters measured in the data studied were root penetration (per cent) and root growth (mm). A regression relation of the form

$$\text{Root growth parameter} = b_1 \ln q_p + c \qquad 6.1$$

was set up, where q_p = soil strength. In these data the matric potential range was quite narrow, so matric potential *per se* would not have been likely to affect root growth. Its effect would be limited to its direct effect on soil strength.

Data studied were:

a) Taylor *et al.* (1966). These authors measured root penetration (%) of cotton in four soils. The matric potential range was -200 to -667 mbar. Soils studied were:

i) Miles loamy fine sand,
ii) Naron fine sandy loam,
iii) Quinlan very fine sandy loam, and
iv) Columbia loam.

Data for the Miles, Quinlan and Columbia soils were obtained from figure 2 of Taylor et al. (1966), while the data for the Naron soil were supplied by Taylor (1974).

b) Taylor and Gardner (1963) measured root penetration (%) of cotton in Amarillo fine sandy loam at matric potentials between -200 and -667 mbar. Data were supplied by Taylor (1974).

c) Cockroft, Barley and Greacen (1969) studied root elongation of peas in Urrbrae fine sandy loam. Data were supplied by Cockroft (1974).

d) Mirreh and Ketcheson (1973) studied root growth of maize in Conestoga clay loam in the matric potential range between -1 and -8 bars. At the lower matric potentials used there would undoubtedly be a moisture effect. A multiple regression model was therefore set up to include matric potential. The model used was:

$$\text{Root growth} = b_1 \ln q_p + b_2 \psi_m + c \qquad 6.2$$

where q_p = soil strength, and ψ_m = matric potential.

The data studied covered a wide range of soil textural classes (17 to 82% silt plus clay), and three different crops, viz. cotton, peas and maize. Individual regression functions and coefficients of determination (R^2) calculated for the data studied are shown in Table 6.1, together with the calculated values of soil strength at which root penetration or root growth is zero. The graph of cotton root penetration versus soil strength for Quinlan, Columbia and Amarillo soils combined is shown in Figure 6.4.

In every case there was a very highly significant semi-logarithmic relationship ($P = 0,001$) between the root growth parameter and soil strength. Most of the variability in root growth was explained by variations in soil strength ($0,648 \leq R^2 \leq 0,915$). In the data of Mirreh and Ketcheson (1973) the multiple regression of root growth on soil strength

TABLE 6.1

Calculated regression functions, significance levels and 'critical' soil strengths for relation:

Root growth parameter = $b_1 \ln q_p + c$

Soil[+]	Calculated regression function	Critical soil strength, bar	R^2
Miles[1]	RP = 113,13 - 37,82 ln q_p	19,9	0,900***
Naron[2]	RP = 117,88 - 37,98 ln q_p	22,3	0,863***
Quinlan[1]	RP = 173,43 - 56,87 ln q_p	21,1	0,914***
Columbia[1]	RP = 162,68 - 52,08 ln q_p	22,7	0,841***
Amarillo[2]	RP = 176,00 - 48,95 ln q_p	36,4	0,915***
Urrbrae[3]	RG = 164,46 - 50,00 ln q_p	26,8	0,648***
	Multiple regression relation: Root growth = $b_1 \ln q_p + b_2 \psi m + c$		
Conestoga[4]	RG = 38,84 - 7,72*** ln q_p + 2,52*** ψm		0,870***

RP = Root penetration, %

RG = Root growth, mm

q_p = Soil strength, bar

ψm = Matric potential, bar

[+]Data from sources shown:

[1]Taylor et al. (1966)

[2]Taylor (1974)

[3]Cockroft (1974)

[4]Mirreh and Ketcheson (1973)

and matric potential was also very highly significant (P = 0,001; R^2 = 0,870), both partial regression coefficients being very highly significant (P = 0,001).

'Critical' soil strengths at which root growth was

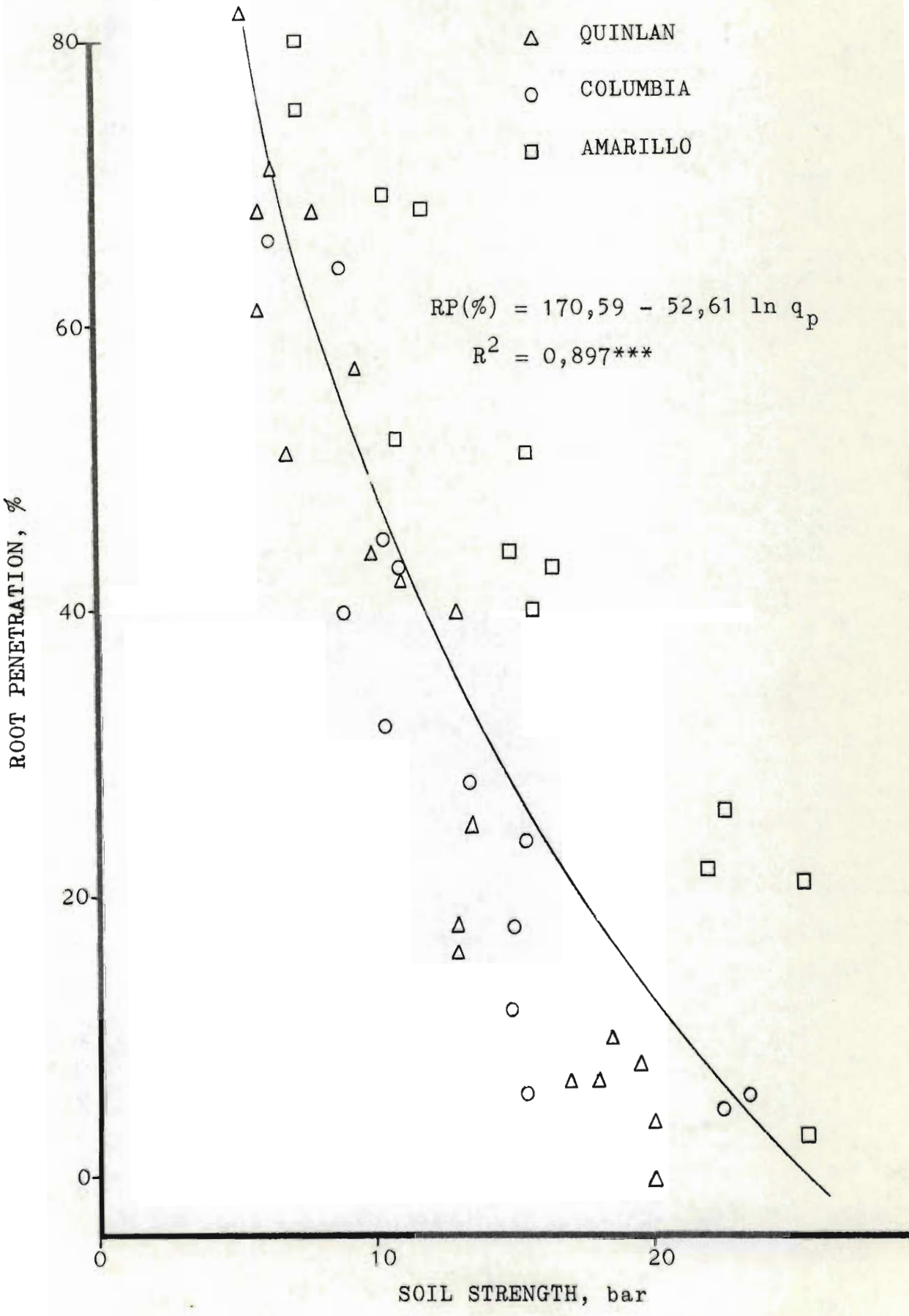

Fig. 6.4 Relation between penetrometer soil strength and percentage of cotton taproots penetrating cores of three soils

calculated to be zero were in the range 19,9 to 36,4 bars. Soil strengths of this order are generally regarded as being limiting to root growth. Taylor and Burnett (1964) found that soil strengths of the order of 25 to 30 bars at 'field capacity' prevented cotton root penetration. Cockroft et al. (1969) found that pea root growth ceased at 24 bars in an aggregated clay. In the tillage trials, soil strengths within the hard layer measured with the field penetrometer were between 16 and 24 bars at 'field capacity', and calculated to be between 25 and 39 bars at -1 000 mbar matric potential.

On the assumption, therefore, that soil strengths of the order of 20 to 30 bars restrict root growth, it appears that root restriction will occur in the hard layers in these tillage trials. In order to determine the effect of these ploughpans on root distribution under natural field conditions, root 'profiles' were extracted from the tillage trials.

6.5.2 Root profiles

Root profiles were extracted from the three tillage depth treatments in the Grasslands tillage trial using a pinboard. The pinboard used was 600 mm by 450 mm deep with 150 mm long pins. A 600 mm deep trench was dug at right angles to the direction of the crop row, and about 75 mm from the stalk of the plant whose root system was being studied. The pinboard was then driven horizontally into the exposed soil face. A hydraulic jack was placed under the pinboard to hold the soil block in place. Narrow trenches were then dug on the remaining three sides of the pinboard, and below it. The soil block was then carefully removed and transported to the laboratory. At the laboratory the root system, held in place by the pins, was exposed by gently washing the soil away using fine water sprays. Once all the soil had been washed away the pinboard was photographed to give an accurate two-dimensional representation of the root system under natural field conditions.

Drawings of root profiles extracted from the three depths of ploughing at Grasslands are shown in Fig. 6.5. Root growth above the hard layer was prolific. Within the hard layer root

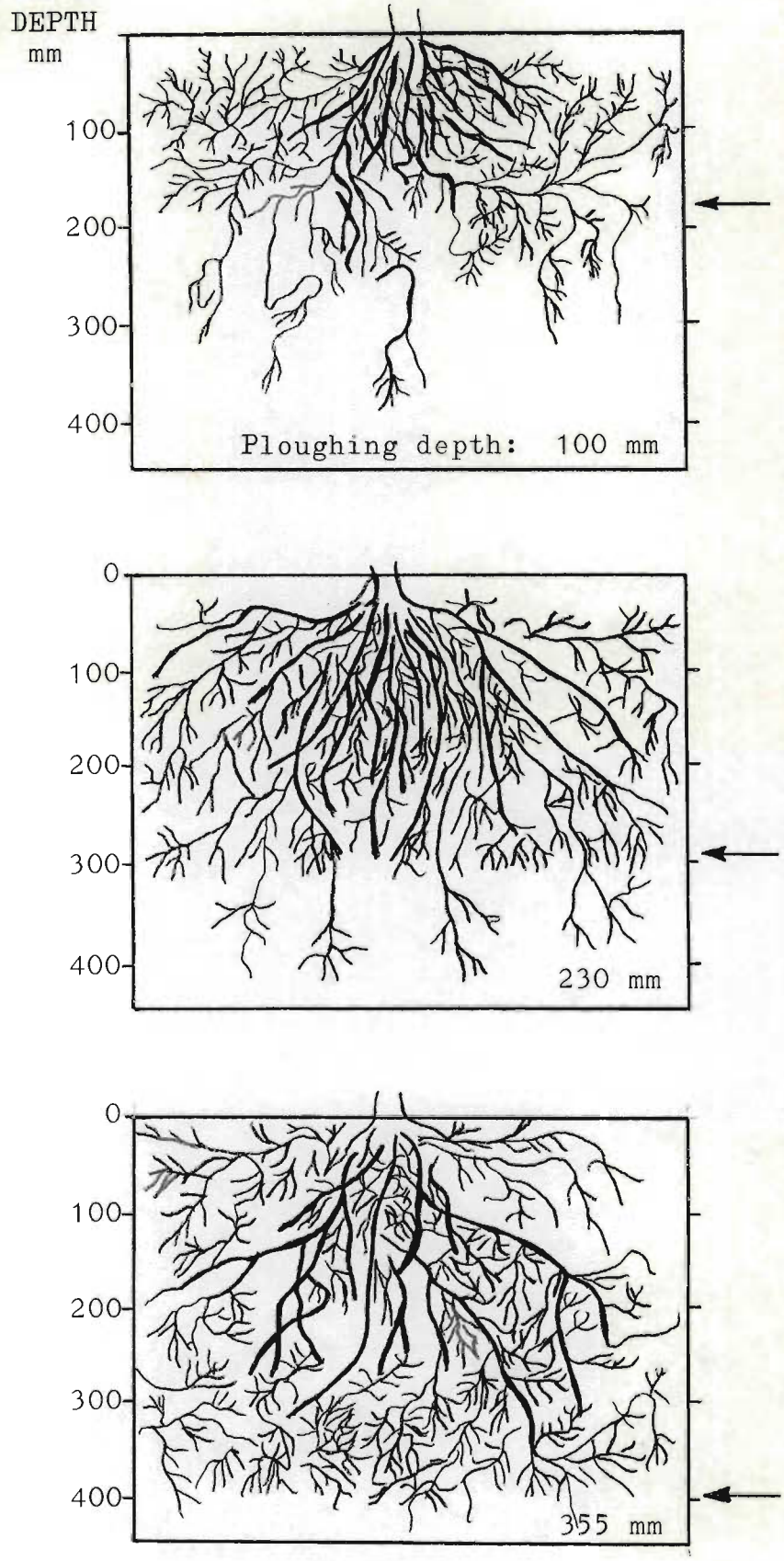

Fig. 6.5 Drawings of root profiles extracted from the three depths of ploughing at Grasslands (the arrows indicate the approximate position of the hard layer

growth, especially of secondary roots was quite severely reduced, while below the pan the roots proliferated once again. The number of roots was closely correlated with soil strength as measured with the field penetrometer (cf. Fig. 6.2).

Consequences of this restricted rooting are a restricted volume from which the plant can draw water and nutrients. This may lead to reduced crop yield, especially in dry seasons when available moisture is likely to be limiting. In order to evaluate the effect of plough pans on yield, maize yield data for the four tillage trials will be analysed.

6.6 Maize yields on the tillage trials

Maize yield data for the individual treatments at the four sites for the seven years during which the differential treatments were imposed are shown in appendix 6.1. These data were produced by the Biometrics Bureau from data supplied by officers responsible for the tillage trials. Maize yields in the 1967 and 1968 seasons at Makoholi were very low (< 1 t ha^{-1}) and were not included in the subsequent analysis.

During analysis of the data it became obvious that there was a marked seasonal effect of the imposed ploughing depth treatments on maize yield, particularly at Domboshawa, Grasslands and Makoholi. A basic subdivision into wet and dry seasons was therefore made. A season was classified 'dry' if a prolonged dry period occurred which would have been likely to reduce yield, or if the seasonal rainfall was below average. A season was classified 'wet' if the dry periods were short and not pronounced, and if the seasonal rainfall was above average. Rainfall data (October to April) for each of the four sites are presented in appendix 6.2. No rainfall figures were recorded at Hatcliffe in 1968 and 1969. The figures presented for these two years are the means of the figures from Domboshawa and Salisbury Research Station, the two nearest stations for which rainfall figures are available.

The season classifications made on the basis of the above

criteria are also included in appendix 6.2. At Hatcliffe there was little evidence of there being any marked seasonal effect of the tillage treatments on maize yield, so no classification of the seasons was made.

6.6.1 Results

Mean maize yield data for the three ploughing depth treatments on the four trials are shown in Table 6.2, together with the mean rainfall figures and the significance levels of the ploughing depth effect on maize yield. The effect of depth of ploughing on yield is illustrated graphically in Fig. 6.6, which shows maize yields for the 230 and 355 mm ploughing depths relative to those for the 100 mm ploughing depth treatment. Three main conclusions can be drawn from these data:

a) the ploughing depth effect was greater in dry seasons (at Domboshawa, Grasslands and Makoholi) than it was in wet seasons,

b) in all cases maize yield was greater on the 230 mm ploughing depth treatment than on the 100 mm, but except at Makoholi there was little difference between the 230 and 355 mm ploughing depth treatments, and

c) the overall ploughing depth effect was greatest at Makoholi and least at Hatcliffe, with the other two intermediate.

The overall effects of compost level at Domboshawa, Grasslands and Makoholi, and of fertilizer level at Hatcliffe are presented in Table 6.3. Overall the effect was significant, with maize yield increasing with level of applied compost or fertilizer. On the three coarse-textured sites the significance of the compost effect was higher in wet seasons than in dry, indicating that better use was being made of the compost when soil moisture was at a more optimal level.

6.6.2 Discussion

Pans present in the tillage trials restrict rooting and thus the volume of soil available to plant roots for the

TABLE 6.2

Mean maize yield (t ha^{-1}), mean rainfall (mm) and significance of ploughing depth effect on maize yield at Domboshawa, Grasslands, Makoholi and Hatcliffe

Ploughing depth mm	DOMBOSHAWA			GRASSLANDS			MAKOHOLI			HATCLIFFE
	Season		Overall	Season		Overall	Season		Overall	Overall
	Dry	Wet		Dry	Wet		Dry	Wet		
100	5,58	8,23	7,47	4,02	8,05	6,33	3,18	5,43	4,08	6,36
230	6,46	8,56	7,96	4,57	8,50	6,82	4,14	6,31	5,01	6,39
355	6,64	8,46	7,94	4,80	8,33	6,82	4,63	6,89	5,53	6,19
Mean	6,23	8,42	7,79	4,46	8,30	6,65	3,99	6,21	4,88	6,31
Mean rainfall[+], mm	617,1	891,5	813,1	642,8	888,7	783,3	484,5	801,0	611,0	851,3
SE	0,104	0,109	0,092	0,188	0,151	0,145	0,228	0,289	0,246	0,148
LSD: 0,05	0,33	0,34	0,29	0,65	0,52	0,50	0,72	0,91	0,77	0,47
0,01	0,47	0,49	0,41	0,98	0,79	0,76	1,02	1,30	1,10	0,66
0,001	0,68	0,70	0,60	1,58	1,27	1,22	1,48	1,88	1,60	0,96
Significance[o]	***	NS	**	NS	NS	NS	**	*	**	NS

[+]Mean rainfall, October to April

[o]Significance of ploughing-depth effect on maize yield

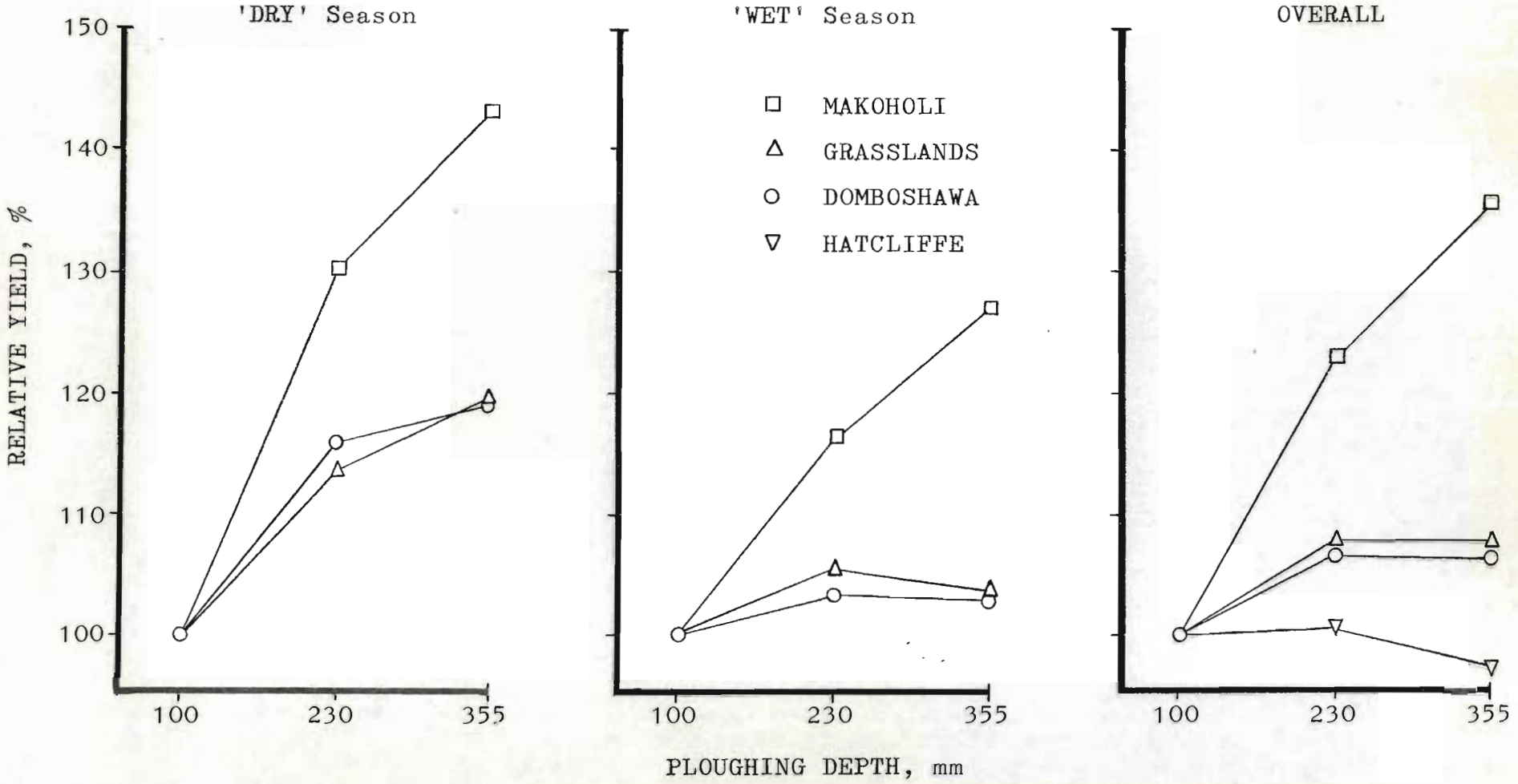

Fig. 6.6 Maize yields on the 230 and 355 mm ploughing depth treatments, relative to those on the 100 mm treatment (=100) at the four tillage trial sites

TABLE 6.3

Mean maize yield (t ha^{-1}), mean rainfall (mm) and significance of compost (fertilizer) effect on maize yield at Domboshawa, Grasslands, Makoholi and Hatcliffe

Compost (fertilizer) level[+]	DOMBOSHAWA			GRASSLANDS			MAKOHOLI			HATCLIFFE
	Season		Overall	Season		Overall	Season		Overall	Overall
	Dry	Wet		Dry	Wet		Dry	Wet		
1	5,91	7,71	7,20	3,75	7,33	5,79	3,81	5,47	4,47	6,11
2	6,22	8,54	7,88	4,69	8,60	6,92	4,12	6,41	5,04	6,34
3	6,55	9,00	8,31	4,96	8,97	7,25	4,03	6,76	5,12	6,48
Mean	6,23	8,42	7,79	4,46	8,30	6,65	3,99	6,21	4,88	6,31
Mean rainfall mm	617,1	891,5	813,1	642,8	888,7	783,3	484,5	801,0	611,0	851,3
SE	0,129	0,066	0,055	0,085	0,106	0,088	0,126	0,186	0,140	0,082
LSD: 0,05	0,37	0,19	0,16	0,25	0,32	0,26	0,36	0,54	0,41	0,24
0,01	0,50	0,26	0,21	0,35	0,43	0,36	0,49	0,72	0,55	0,32
0,001	0,66	0,34	0,28	0,48	0,59	0,49	0,65	0,96	0,72	0,42
Significance[o]	**	***	***	***	***	***	NS	***	**	*

[+]See footnotes appendix 6.1 for compost (fertilizer) levels

[o]Significance of applied compost (fertilizer) on maize yield

extraction of water and nutrients.

Considering first the effect of reduced rooting volume on the availability of nutrients in these soils Grant (1968, and unpublished data) has shown that most of the nutrients are concentrated within the ploughed zone. Furthermore, although depth of ploughing affects the distribution of roots - most of the roots being within the ploughed zone, it does not seem to affect the total mass of roots (Grant, 1968); thus both roots and nutrients are concentrated within the ploughed zone.

Considering plant available water above the hard layer, there are marked differences between the three ploughing depth treatments, particularly on the three coarse-textured soils. Table 6.4 shows available water, above the hard layer, calculated as the difference between water held at 'field capacity' and at -5 bars matric potential, multiplied by the depth to the hard layer, with the data expressed in mm.

TABLE 6.4

Available water (mm) in the three ploughing depth treatments at Domboshawa, Grasslands, Makoholi and Hatcliffe

Ploughing depth, mm	Site			
	Domboshawa	Grasslands	Makoholi	Hatcliffe
100	8,7	8,5	11,1	26,2
230	19,5	26,0	21,5	28,1
355	28,1	29,1	28,4	31,7
SE	0,51	1,09	0,76	0,78
LSD: 0,05	1,6	3,8	2,4	2,5
0,01	2,3	5,7	3,4	3,5
0,001	3,3	9,2	4,9	5,1
Significance	***	***	***	**

On the three coarse-textured soils, available water on the 100 mm ploughing depth treatments was very low, but increased with depth of ploughing. At Hatcliffe the difference in

available water between the three ploughing depth treatments, although significant, was quite small.

These available water data explain to a large degree the conclusions drawn in section 6.6.1 from the maize yield data. One factor which is not explained by the available soil water data is that on the coarse-textured soils the ploughing depth effect is greater at Makoholi than at the other two sites. Table 6.2 shows that available soil water at the three sites is quite similar; however two environmental factors reduce the net amount of water available to the maize crop at Makoholi. Firstly, mean rainfall at Makoholi at 611 mm, was considerably lower than the 783 mm at Grasslands, and 813 mm at Domboshawa. Secondly evaporation figures at Makoholi are higher than those at Grasslands (no data are available for Domboshawa). Class 'A' screened pan evaporation figures calculated from graphs presented by Torrance (1970) give a mean daily evaporation over the period October to April of 6,05 mm at Makoholi, and 5,11 mm at Grasslands, with evaporative demand during December and January being 25 to 30% higher at Makoholi. Thus, lower mean rainfall and higher mean evaporative demand combine to reduce the net amount of soil water available at Makoholi to the crop, and explains the greater dependence of maize yield on depth of ploughing at Makoholi than at the other two coarse-textured sites.

6.7 Conclusions

Pans with high soil strength, shown in chapter 4 to exist in the tillage trials have arisen due to particle rearrangement within the soil fabric. This has been caused by a combination of interacting factors, viz. previous history of the soils, compaction of the soil during ploughing operations, and as a result of swelling and shrinkage of soil constituents during wetting and drying. These particle rearrangement processes cause an increase in the number of interparticle contacts and therefore an increase in soil strength.

A study of root growth/soil strength data obtained by several

authors on three different test crops showed that root growth was halted at soil strengths of between 20 and 30 bars. Soil strengths of this order have been shown to exist within the hard layers of the soils studied in this investigation, and root profiles extracted from the Grasslands tillage trial show that these hard layers severely limit the zone of root proliferation.

On the three coarse-textured sites (Domboshawa, Grasslands and Makoholi) maize yield increased with increased depth of ploughing, and there was a marked seasonal effect, ploughing depth having a relatively greater effect on maize yield in dry seasons than in wet. At Hatcliffe, however, where no pan existed near the surface in the shallow ploughed treatment, the ploughing depth effect was not significant, nor was there any marked seasonal effect of ploughing depth on maize yield. These findings, together with the data for available soil moisture, indicate that soil moisture is probably the major factor limiting maize yield in these soils.

In conclusion it is pertinent to cite some of the findings of Taylor, Locke and Box (1964a) from their research on the effects of pans on crop yield, and see how they compare with the findings in this investigation. These authors found that increases in soil strength from 5 to 25 bars at field capacity caused progressive decreases in rate of plant growth and yield. Pans near the soil surface reduced yield more often and more severely than did those deeper in the profile. The reasons for this were that plant roots encounter pans near the soil surface sooner than those deeper in the profile, and that pans near the soil surface undergo changes in soil moisture more often and more rapidly than deeper pans. These two factors combine to enhance the effect of shallow pans. Crop yield would be reduced more severely, on a relative basis, during a drought year than during a normal rainfall year, because drought enhances strength of pans more than that of adjacent layers. These findings are in close agreement with the findings of this investigation.

GENERAL DISCUSSION

The tillage trials studied in this investigation were ploughed continuously to three specified depths for seven years. The objectives of the study undertaken in this thesis were:

1) to evaluate the effect of the imposed treatments on soil physical parameters,
2) to establish which soil physical factor, or factors were restricting root growth, and
3) to determine the effects of these physical factors on root growth and maize yield.

At the outset soil physical parameters considered most likely to affect root growth and maize yield in these soils were soil aeration, soil strength and available soil moisture. Techniques chosen to be the most suitable for measuring these three physical parameters were:

1) soil aeration - measurement of oxygen flux using the platinum microelectrode,
2) soil strength - resistance to penetration measured with the penetrometer, and
3) available moisture - measured as the difference between water held at 'field capacity' and -5 bar matric potential.

Considerable problems were encountered at the outset with the platinum microelectrode technique for measuring oxygen flux, so it was decided to investigate the method with a view to improving the instrumentation and methodology. The technique was developed initially for measuring oxygen flux in two-phase (soil-water) systems. It was subsequently used for measuring oxygen flux in three-phase (soil-water-air) systems; its users tacitly assuming that conditions prevailing in two-phase systems also prevailed in three-phase systems. McIntyre (1970) has shown that this is not so.

The basic problem with the measurement of oxygen flux in three-phase (unsaturated) systems is that current flow due to oxygen reduction at the electrode is not diffusion controlled,

because of activation and concentration polarization. This means that measured current is continuously dependent upon applied potential, and unless applied potential is very carefully controlled, erroneous current readings will be obtained. Existing instrumentation did not meet this requirement. A new instrument was therefore designed and built. This instrument fulfilled the requirement for careful current control, and contained the circuitry necessary for measuring soil resistance. This latter point assumes importance in unsaturated soils if results are to be compared within and between soils.

The need to pretreat platinum microelectrodes, so that they have reproducible surface oxide conditions, was demonstrated in an experiment in which current measured in a standard medium was related to electrode potential (a measure of the surface oxide condition). Regression relations showed a very highly significant correlation between measured current and electrode potential. A simple method for electrode pretreatment, viz. abrasion in sand was developed and used for producing standard surface oxide conditions on the electrodes. The technique proved to be quick and highly reproducible.

Oxygen flux index was then measured in four soil samples with widely differing particle size and, consequently, pore size distributions. Oxygen flux index was quite high at saturation, decreased to a minimum at about 3% air space, and then increased linearly with air space up to about 15% air space. The linear regression relationship between oxygen flux index and air space in the range 3 - 15% air space was very highly significant ($R^2 = 0,963$), with the between soils regression being non-significant. This led to the decision that air space was a suitable index of soil aeration, and so it was used subsequently instead of the rather more tedious measurement of oxygen flux index.

Although the platinum microelectrode technique for measuring oxygen flux was not used subsequently in this investigation, the technique, as described in this thesis should find widespread use for measuring soil aeration in saturated

and near-saturated soils.

The second soil physical factor considered likely to affect root growth was soil strength. This parameter has been shown by several authors (Taylor and Gardner, 1963, and Taylor and Burnett, 1964) to be a more useful index to relate to root growth than is bulk density. A field penetrometer which measures soil strength continuously down to a depth of 600 mm in field soils is described. Measurements made on the four tillage trials showed that high soil strength pans existed in all the treatments, and that with the exception of the shallowest ploughing depth treatment at Hatcliffe, the hard layers were between a few mm and 150 mm below the nominal ploughing depth. At Hatcliffe the hard layer was approximately 225 mm below the nominal ploughing depth (100 mm). The pans all had strengths of between 16 and 24 bars at 'field capacity'.

The pans showed many of the characteristics of tillage pans, but their existence could not be attributed exclusively to the imposed ploughing depth treatments. Rather, the pans resulted from a combination of interacting factors, viz. the previous history of the soils, the imposed tillage treatments, crop and climatic factors.

In order to investigate more closely the physical factors affecting soil strength, the basic theory of needle penetrometers was studied, and a laboratory penetrometer which was designed taking into account these theoretical considerations, is described. Data obtained on undisturbed cores showed that soil strength was highly dependent upon bulk density, matric potential and soil texture.

A comprehensive range of undisturbed cores was taken at various depths within each treatment from each of the four tillage trials and subjected to extensive physical measurements in the laboratory to determine the effects of continuous ploughing to specified depths on soil physical parameters. Parameters measured were soil strength, air space at high matric potential, bulk density, soil texture and available moisture. Aeration status of the soils was adequate, air space being

above 14% at all levels in all the soils at 'field capacity'. Even at -20 mbar matric potential air space was above 9% everywhere. Available soil moisture increased with increased silt plus clay content, so Makoholi had the lowest available moisture and Hatcliffe the highest. Soil strengths measured in the laboratory corresponded closely with those measured with the field penetrometer. From the field and laboratory measurements it was concluded that soil strength was the factor most likely to restrict root growth in these soils. Root profiles extracted from the three ploughing depth treatments at Grasslands confirmed this.

Maize yield data showed that on the three coarse-textured soils (Domboshawa, Grasslands and Makoholi), yield increased with increased depth of ploughing, and that there was a marked seasonal effect, ploughing depth having a relatively greater effect on maize yield in dry seasons than in wet. At Hatcliffe, however, where no pan existed near the surface in the shallow ploughed treatment, the ploughing depth effect was not significant, nor was there any significant seasonal effect of ploughing depth on maize yield. These findings, together with the data for available soil moisture, indicate that high soil strength pans, by limiting rooting depth and thus the amount of water available to the plant, are limiting maize yields in these soils.

The solution to the problems caused by the development of pans would be the introduction of a tillage rotation system in which shallow ploughing, deep ploughing and ripping were used in rotation. There is little information at present on how quickly tillage pans develop within the soil; the rate of development would be highly dependent upon the soil itself and several external factors, in particular soil moisture at ploughing, crop and climatic factors. Nevertheless, it would be relatively easy to follow the development of hard layers using the field penetrometer, and these measurements could be used to improve the quality and efficiency of tillage practices.

APPENDIX 2.1

Electrode potential-reduction current readings for four electrodes with two initial surface conditions

Electrode 2		Electrode 8		Electrode 11		Electrode 14	
Electrode potential V, mV	Reduction current i, μA	Electrode potential V, mV	Reduction current i, μA	Electrode potential V, mV	Reduction current i, μA	Electrode potential V, mV	Reduction current i, μA
1) 'Clean' electrodes							
282	2,45	272	2,40	291	2,55	266	2,52
277	2,41	264	2,35	285	2,51	264	2,49
274	2,35	259	2,30	283	2,45	262	2,44
271	2,32	256	2,26	281	2,41	259	2,42
267	2,28	253	2,24	274	2,38	254	2,37
2) 'Aged' electrodes							
196	2,17	177	1,97	203	2,21	178	2,12
143	1,92	116	1,78	158	2,05	155	1,96
114	1,86	104	1,72	123	1,91	129	1,87
92	1,78	89	1,65	102	1,85	103	1,82
86	1,68	84	1,61	93	1,80	97	1,76

APPENDIX 2.2

Regression analysis of electrode potential-reduction current for electrodes with two initial surface conditions

Analysis of variance of current

Source	DF	SS	MS	F
Overall line	1	0,434 029	0,434 029	775,05***
Between condition slopes	1	0,025 248	0,008 416	15,03***
Between electrode slopes	3	0,000 611	0,000 204	< 1 NS
C x E slopes	3	0,001 272	0,000 424	< 1 NS
Within sets error	24	0,013 440	0,000 560	
Total within sets	32	0,474 600		

Regression equations:

Clean electrodes: $i = 0,010\ 44V - 0,422$

$R^2 = 0,934***$

Aged electrodes: $i = 0,003\ 85V + 1,385$

$R^2 = 0,973***$

NOTE: Throughout this thesis the following connotations are used for significance levels:

* P = 0,05 - significant

** P = 0,01 - highly significant

*** P = 0,001 - very highly significant.

APPENDIX 2.3

Electrode potential–reduction current readings for five electrodes measured 12 times in two days

Electrode 2		Electrode 4		Electrode 8		Electrode 11		Electrode 14	
Electrode potential mV	Reduction current µA	Electrode potential mV	Reduction current µA	Electrode potential mV	Reduction current µA	Electrode potential mV	Reduction current µA	Electrode potential mV	Reduction current µA
1) Day 1									
285+	2,50+	275+	2,70+	280+	2,30+	290+	2,60+	260+	2,55+
300	2,55	280	2,75	295	2,40	305	2,70	280	2,60
300	2,55	280	2,80	300	2,40	300	2,70	295	2,60
300	2,55	285	2,75	290	2,40	300	2,70	295	2,60
300	2,55	285	2,75	295	2,40	305	2,70	295	2,65
310	2,55	295	2,75	305	2,40	305	2,70	295	2,60
2) Day 2									
295+	2,60+	280+	2,85+	300+	2,45+	300+	2,70+	240+	2,65+
300	2,55	280	2,80	295	2,45	300	2,70	280	2,60
300	2,55	275	2,75	295	2,45	295	2,70	285	2,60
300	2,55	275	2,75	295	2,45	295	2,70	285	2,60
295	2,55	275	2,75	290	2,45	295	2,65	285	2,60
295	2,50	275	2,75	285	2,45	290	2,65	280	2,60

+Readings rejected in subsequent analysis (see text)

CV = 0,78%

APPENDIX 2.4

Regression analysis of relationship between oxygen flux index (OFI) and air space in the range 3-15% air space for four soils

Analysis of variance				
Source	DF	SS	MS	F
Regression	1	1 913,8238	1 913,82	223,51***
Between soils	3	13,5281	4,51	<1 NS
Error	7	59,9390	8,5627	
Total	11	1 987,2909		

Regression equation

$$OFI = 2{,}90 \text{ (air space)} - 8{,}32$$

$$R^2 = 0{,}963***$$

APPENDIX 3.1

Calculated and measured gauge readings over a period of five months during calibration of a field penetrometer

Calculated reading	Dates of measurement					Mean reading
	11/71	12/71	1/72	2/72	3/72	
7,4	7,8	8,0	7,8	8,0	7,5	7,8
14,7	15,7	15,8	15,5	16,0	15,2	15,6
22,1	22,8	23,2	22,8	24,0	23,0	23,2
29,4	30,0	30,3	30,0	31,2	30,4	30,4
36,8	37,7	38,5	37,3	38,4	37,9	38,0
44,2	44,5	44,8	44,7	46,0	45,2	45,0
51,5	52,0	52,0	51,7	53,2	52,2	52,2
58,9	59,0	59,0	59,0	60,1	59,9	59,4

Regression analysis of variance

Source	DF	SS	MS	F
Regression	1	11 336,46	11 336,46	***
Between times	4	1,20	0,30	2,52 NS
Error	30	3,57	0,1190	
Total	35	11 341,23		

Regression relation: Calculated reading (x) versus Measured reading (y)

$$y = 0,998x + 0,87$$

$$R^2 = 0,9996***$$

APPENDIX 4.1
Details of tillage trials

SITES: a) Domboshawa: Domboshawa Training School, north of Salisbury, land on main entrance road near school kitchen.
b) Grasslands: Grasslands Research Station, west of Marandellas, in Trollip's triangle.
c) Makoholi: Makoholi Experiment Station, north of Fort Victoria, in Block 01.
d) Hatcliffe: Agricultural Engineering Centre at Hatcliffe Estate, north of Salisbury. Land at the end of the experimental block below the offices.

SOILS: a) Domboshawa: sandy loam changing to sandy clay loam at about 300 mm. Derived from granite.
b) Grasslands: loamy sand/sandy loam changing to slightly 'heavier' sandy loam at about 300 mm. Derived from granite.
c) Makoholi: deep sand. Derived from granite.
d) Hatcliffe: sandy clay loam changing to sandy clay at about 300 mm. Derived from banded ironstone.

The three granite-derived soils are para-ferrallitic, as defined by Thompson (1965), and their clay fractions consist practically entirely of kaolinite and amorphous sesquioxides of iron and aluminium. The Hatcliffe soil is fersiallitic, the clay fraction being predominantly kaolinite, but with some 2:1 lattice minerals.

CROP: Continuous maize, fertilized to yield between 4,5 and 5,6 t ha^{-1} at Makoholi and between 6,7 and 7,8 t ha^{-1} at Domboshawa, Grasslands and Hatcliffe. At Domboshawa, Grasslands and Makoholi stover was removed from the plots, while at Hatcliffe the stover was incorporated.

TREATMENTS: Depth of ploughing: 100, 230 and 355 mm
Type of plough: mouldboard and disc
Compost levels applied at Domboshawa, Grasslands

APPENDIX 4.1 (continued)

and Makoholi: 0; 5 and 10 t ha^{-1} (DM) per season
Fertilizer levels applied before ploughing at Hatcliffe: 0; 112 kg compound G + 112 kg lime per ha; 224 kg compound G + 224 kg lime per ha.

DESIGN: 3 x 2 x 3 split-plot factorial. At Domboshawa, Makoholi and Hatcliffe there were six replicates arranged in six randomised blocks, and at Grasslands there were four replicates arranged in four randomised blocks. The treatment combinations of depth of ploughing and type of plough occupied the main plots, with the rates of compost or fertilizer accommodated by splitting each main plot into three sub-plots. These latter treatments were arranged at random within each of the main plots.

APPENDIX 4.2

Depths of sampling for undisturbed cores from the Domboshawa, Grasslands, Makoholi and Hatcliffe tillage trials

a) Zero compost, disc ploughed plots at Domboshawa, Grasslands and Makoholi

Depth of sample	Ploughing depth		
	100 mm	230 mm	355 mm
1	75 - 150	75 - 150	75 - 150
2 Depth of	150 - 225	250 - 325	250 - 325
3 sample, mm	225 - 300	325 - 400	400 - 475
4	350 - 425	400 - 475	475 - 550

Domboshawa : six replicates sampled = 72 cores
Grasslands : four replicates sampled = 48 cores
Makoholi : six replicates sampled = 72 cores

b) 10 t ha^{-1} compost, disc ploughed plots at Grasslands

Six cores on each replicate, corresponding to depths of sampling 2 and 3 on each ploughing depth treatment above. Total of 24 cores.

c) Zero fertilizer, disc ploughed plots at Hatcliffe

Six cores taken on each treatment, depths of sampling identical in each treatment.

Depth of sample	Depth of sampling, mm
1	75 - 150
2	150 - 225
3	225 - 300
4	300 - 375
5	375 - 450
6	450 - 525

Six replicates sampled = 108 cores

APPENDIX 4.3.1

Particle size distribution

DOMBOSHAWA

Ploughing depth, mm	Depth of sample	Clay %	Silt %	Sand %	Sand %			Textural class
					Coarse	Medium	Fine	
	1	11,8	3,5	84,7	17,2	36,9	30,6	SaLm
	2	13,3	3,4	83,3	17,1	33,2	33,0	SaLm
100	3	21,4	3,1	75,5	14,6	26,1	34,8	SaClLm
	4	25,5	4,6	69,9	12,6	21,5	35,8	SaClLm
	1	14,2	2,8	83,0	17,8	32,4	32,8	SaLm
	2	18,4	2,6	79,0	17,1	27,4	34,5	SaLm
230	3	24,6	4,2	71,2	12,4	21,6	37,2	SaClLm
	4	24,8	4,4	70,8	12,8	20,9	37,1	SaClLm
	1	16,3	2,5	81,2	17,1	31,5	32,6	SaLm
	2	16,5	2,4	81,1	17,2	31,3	32,6	SaLm
355	3	22,7	3,8	73,5	14,3	23,6	35,6	SaClLm
	4	24,3	4,4	71,3	11,5	20,8	39,0	SaClLm

Particle size classes:

Clay	$< 0,002$ mm	Fine sand	0,02 - 0,2 mm
Silt	0,002 - 0,02 mm	Medium sand	0,2 - 0,5 mm
Sand	0,02 - 2,0 mm	Coarse sand	0,5 - 2,0 mm

APPENDIX 4.3.2

Particle size distribution

GRASSLANDS

Ploughing depth, mm	Depth of sample	Clay %	Silt %	Sand %	Sand %			Textural class
					Coarse	Medium	Fine	
	1	9,6	2,7	87,7	35,5	32,7	19,5	LmSa
	2	12,2	2,2	85,6	34,3	30,9	20,4	SaLm
100	3	15,0	2,4	82,6	33,6	25,9	23,1	SaLm
	4	16,5	4,4	79,1	30,2	21,8	27,1	SaLm
	1	13,4	2,8	83,8	31,6	28,8	23,4	SaLm
	2	15,2	2,6	82,2	30,0	27,2	25,0	SaLm
230	3	18,5	4,2	77,3	27,1	20,7	29,5	SaLm
	4	19,1	3,8	77,1	25,8	20,2	31,1	SaLm
	1	12,7	2,4	84,9	35,5	27,9	21,5	SaLm
	2	13,0	2,1	84,9	34,8	27,2	22,9	SaLm
355	3	18,9	3,9	77,2	30,1	18,9	28,2	SaLm
	4	17,8	4,9	77,3	29,5	18,6	29,2	SaLm

APPENDIX 4.3.3

Particle size distribution

MAKOHOLI

Ploughing depth mm	Depth of sample	Clay %	Silt %	Sand %	Sand %			Textural class
					Coarse	Medium	Fine	
	1	2,0	2,8	95,2	33,6	34,8	26,8	Sa
	2	2,3	2,5	95,2	33,4	34,8	27,0	Sa
100	3	2,4	3,1	94,5	34,9	32,4	27,2	Sa
	4	2,8	2,9	94,3	33,7	31,7	28,9	Sa
	1	2,2	2,4	95,4	33,5	35,3	26,6	Sa
	2	2,7	2,3	95,0	32,6	35,1	27,3	Sa
230	3	3,1	2,6	94,3	33,2	33,4	27,7	Sa
	4	3,1	2,9	94,0	33,3	32,5	28,2	Sa
	1	2,7	2,7	94,6	32,0	35,0	27,6	Sa
	2	2,7	2,9	94,4	31,8	35,3	27,3	Sa
355	3	3,3	2,9	93,8	33,1	32,6	28,1	Sa
	4	3,7	2,8	93,5	32,5	32,0	29,0	Sa

APPENDIX 4.3.4

Particle size distribution

HATCLIFFE

Ploughing depth, mm	Depth of sample	Clay %	Silt %	Sand %	Sand %			Textural class
					Coarse	Medium	Fine	
	1	26,7	14,1	59,2	3,1	4,5	51,6	SaClLm
	2	28,6	12,6	58,8	3,7	4,7	50,4	SaClLm
	3	34,2	10,9	54,9	3,0	3,3	48,6	SaClLm
100	4	36,9	10,0	53,1	2,5	2,5	48,1	SaCl
	5	39,2	11,2	49,6	2,5	2,5	44,6	SaCl
	6	38,3	11,3	50,4	2,3	2,4	45,7	SaCl
	1	27,6	12,8	59,6	3,9	4,7	51,0	SaClLm
	2	27,3	12,1	60,6	3,5	4,8	52,3	SaClLm
	3	30,0	11,3	58,7	3,9	4,7	50,1	SaClLm
230	4	33,8	11,7	54,5	3,4	3,2	47,9	SaClLm
	5	38,0	11,3	50,7	2,3	2,4	46,0	SaCl
	6	38,0	11,3	50,7	2,3	2,5	45,9	SaCl
	1	29,1	11,6	59,3	4,1	4,3	50,9	SaClLm
	2	28,3	11,7	60,0	3,5	3,9	52,6	SaClLm
	3	28,5	12,4	59,1	3,8	4,2	51,1	SaClLm
355	4	30,5	11,2	58,3	4,0	4,2	50,1	SaClLm
	5	35,6	11,9	52,5	3,2	3,3	46,0	SaCl
	6	37,2	11,2	51,6	2,3	2,4	46,9	SaCl

APPENDIX 6.1.1

Maize yield (t ha^{-1}) DOMBOSHAWA

Treatment code+	Year							Mean
	1965	1966	1967	1968	1969	1970	1971	
121	9,71	7,79	3,78	8,60	6,12	6,26	5,14	6,77
122	10,07	8,43	4,59	9,67	6,34	6,51	7,70	7,62
123	10,08	9,02	5,09	9,88	6,92	7,25	7,95	8,03
Mean	9,96	8,41	4,49	9,38	6,46	6,67	6,93	7,47
221	9,24	8,50	5,75	8,58	6,88	6,42	5,87	7,32
222	9,54	9,21	5,95	9,47	7,20	7,26	7,38	8,00
223	10,02	9,33	6,22	10,60	7,31	7,19	9,33	8,57
Mean	9,60	9,02	5,97	9,55	7,13	6,96	7,53	7,96
321	9,22	8,78	5,92	8,75	6,97	7,32	5,51	7,50
322	9,18	9,14	6,15	9,84	7,22	6,88	7,68	8,01
323	9,28	9,29	6,22	10,54	7,39	7,35	8,13	8,31
Mean	9,23	9,07	6,10	9,71	7,19	7,18	7,11	7,94
-21	9,39	8,36	5,15	8,64	6,66	6,67	5,51	7,20
-22	9,60	8,93	5,56	9,66	6,92	6,88	7,59	7,88
-23	9,80	9,21	5,84	10,34	7,21	7,26	8,47	8,30
Mean	9,59	8,83	5,52	9,55	6,93	6,94	7,19	7,79

+Treatment code:

Ploughing depth (1st digit)	Type of plough (2nd digit)	Compost (3rd digit)
1 = 100 mm	1 = mouldboard	1 = Nil
2 = 230 mm	2 = disc	2 = 5 t ha^{-1} D.M.
3 = 355 mm		3 = 10 t ha^{-1} D.M.

APPENDIX 6.1.2

Maize yield (t ha^{-1}) GRASSLANDS

Treatment code+	Year							Mean
	1965	1966	1967	1968	1969	1970	1971	
121	8,69	6,92	3,60	5,23	3,19	2,07	6,07	5,11
122	9,34	7,72	4,33	9,32	5,26	4,30	8,60	6,98
123	9,04	7,86	4,06	9,44	5,05	4,35	8,44	6,89
Mean	9,02	7,50	4,00	8,00	4,50	3,57	7,70	6,33
221	8,34	6,87	3,70	8,24	4,63	4,03	7,97	6,26
222	8,32	7,83	3,65	9,35	5,74	4,88	9,27	7,01
223	8,59	7,82	3,73	10,00	5,85	4,94	9,42	7,19
Mean	8,41	7,51	3,69	9,20	5,41	4,62	8,89	6,82
321	8,68	7,00	3,88	6,80	4,62	3,98	7,10	6,01
322	8,57	7,54	4,14	8,31	5,23	4,62	8,98	6,77
323	8,96	8,32	4,17	10,50	6,48	6,06	9,23	7,67
Mean	8,74	7,62	4,06	8,54	5,45	4,89	8,44	6,82
-21	8,57	6,93	3,73	6,76	4,15	3,36	7,05	5,79
-22	8,74	7,70	4,04	8,99	5,41	4,60	8,95	6,92
-23	8,86	8,00	3,98	9,98	5,79	5,12	9,03	7,25
Mean	8,72	7,54	3,92	8,58	5,12	4,36	8,34	6,65

+see footnote in appendix 6.1.1 for explanation of code

APPENDIX 6.1.3

Maize yield (t ha^{-1}) MAKOHOLI

Treatment code+	Year							Mean[1]
	1965	1966	1967	1968	1969	1970	1971	
121	3,27	3,98	1,28	0,77	2,63	3,60	5,87	3,87
122	2,85	4,82	0,89	0,58	2,93	4,08	6,68	4,27
123	2,31	4,47	0,70	0,41	2,98	4,01	6,76	4,11
Mean	2,81	4,42	0,96	0,59	2,85	3,90	6,44	4,08
221	5,25	4,50	0,74	0,38	2,80	3,44	6,24	4,45
222	5,63	5,46	0,60	0,55	3,35	4,14	7,57	5,23
223	5,34	6,29	0,31	0,30	3,32	4,00	7,82	5,36
Mean	5,40	5,42	0,55	0,41	3,16	3,86	7,21	5,01
321	6,53	5,16	0,38	0,26	2,81	3,91	7,04	5,09
322	6,63	5,53	0,31	0,27	3,13	4,34	8,42	5,61
323	6,65	6,35	0,24	0,15	3,24	4,42	8,83	5,90
Mean	6,60	5,68	0,31	0,22	3,06	4,23	8,10	5,53
-21	5,02	4,55	0,80	0,47	2,75	3,65	6,38	4,47
-22	5,04	5,27	0,60	0,47	3,15	4,19	7,55	5,04
-23	4,77	5,70	0,42	0,29	3,18	4,15	7,80	5,12
Mean	4,94	5,17	0,61	0,41	3,02	3,99	7,25	4,88

+see footnote in appendix 6.1.1 for explanation of code

[1]1967 and 1968 yields excluded (see text)

APPENDIX 6.1.4

Maize yield (t ha^{-1}) HATCLIFFE

Treatment code+	Year							Mean
	1968	1969	1970	1971	1972	1973	1974	
121	7,14	3,50	6,74	3,31	5,09	9,08	6,72	5,94
122	7,33	3,60	7,02	4,34	5,77	9,41	7,20	6,38
123	7,55	4,09	7,40	5,08	5,73	9,55	7,83	6,75
Mean	7,34	3,73	7,05	4,25	5,53	9,35	7,25	6,36
221	8,61	3,76	7,08	3,88	4,82	9,04	7,50	6,39
222	8,48	3,75	6,96	3,26	4,94	9,52	7,48	6,34
223	8,25	3,80	7,06	3,98	5,54	9,24	7,28	6,45
Mean	8,45	3,77	7,03	3,71	5,10	9,27	7,42	6,39
321	8,76	2,93	6,77	2,58	4,59	8,70	7,74	6,01
322	8,26	3,44	6,77	3,19	5,32	9,30	7,84	6,30
323	8,13	3,40	6,79	3,03	5,14	9,35	7,90	6,25
Mean	8,38	3,26	6,78	2,93	5,02	9,12	7,83	6,19
-21	8,17	3,40	6,86	3,26	4,84	8,94	7,32	6,11
-22	8,02	3,60	6,92	3,60	5,34	9,41	7,51	6,34
-23	7,98	3,76	7,08	4,03	5,47	9,38	7,67	6,48
Mean	8,06	3,58	6,95	3,63	5,22	9,24	7,50	6,31

+see footnote in appendix 6.1.1 for explanation of code

Fertilizer level at ploughing

(3rd digit)

1 = Nil

2 = 112 kg compound G + 112 kg lime per ha

3 = 224 kg compound G + 224 kg lime per ha

APPENDIX 6.2.1

Rainfall (mm) and season classification

DOMBOSHAWA

Month	Season							Mean 1965-71
	1965	1966	1967	1968	1969	1970	1971	
Oct.	27,9	0,0	9,7	0,0	105,4	4,1	15,2	23,2
Nov.	189,7	59,2	33,5	100,6	23,4	204,7	112,5	103,4
Dec.	73,7	136,9	130,8	151,4	432,6	87,6	102,9	159,4
Jan.	128,0	244,3	120,4	395,5	173,7	246,6	275,6	226,3
Feb.	272,5	245,6	117,1	80,3	39,1	96,5	118,6	138,5
Mar.	97,5	225,3	43,2	123,2	22,9	29,0	228,6	110,0
April	60,5	24,1	13,2	30,2	67,6	97,8	72,9	52,3
Total	849,8	935,4	467,9	881,2	864,7	766,3	926,3	813,1
Season classification	Wet	Wet	Dry	Wet	Wet	Dry	Wet	-

APPENDIX 6.2.2

Rainfall (mm) and season classification

GRASSLANDS

Month	Season							Mean 1965-71
	1965	1966	1967	1968	1969	1970	1971	
Oct.	54,6	2,3	25,4	0,5	137,7	3,0	36,8	37,2
Nov.	169,2	45,2	55,4	199,4	76,5	250,2	165,7	137,4
Dec.	35,3	136,4	169,4	144,5	303,8	149,6	197,5	162,4
Jan.	128,5	273,1	30,7	212,3	101,3	203,5	236,9	169,5
Feb.	274,1	284,2	78,7	29,0+	17,3	77,6	187,9	135,5
Mar.	92,7	39,4	8,1	247,1	27,2	30,0	126,3	81,5
April	68,6	16,3	86,6	55,4	65,5	31,0	95,4	59,8
Total	823,0	796,9	454,3	888,2	729,3	744,9	1046,5	783,3
Season classification	Wet	Wet	Dry	Wet	Dry	Dry	Wet	-

+Trial received extra 15 mm of rain not received at recording site

APPENDIX 6.2.3

Rainfall (mm) and season classification — MAKOHOLI

Month	Season							Mean 1965-66, 69-71
	1965	1966	1967	1968	1969	1970	1971	
Oct.	23,1	1,3	66,8	1,0	65,8	0,5	9,2	20,0
Nov.	103,1	79,8	18,5	64,5	92,2	128,0	146,4	109,9
Dec.	16,5	280,7	93,7	238,0	172,2	81,3	75,5	125,2
Jan.	126,7	178,1	13,0	82,8	19,1	198,4	322,9	169,0
Feb.	194,3	119,1	95,0	19,1	21,3+	44,0	187,0	113,1
Mar.	67,1	35,1	16,8	260,6	11,9	13,3	54,7	36,4
April	8,4	30,0	20,3	69,9	30,0	36,2	82,2	37,4
Total	539,2	724,1	324,1	735,9	412,5	501,7	877,9	611,0
Season classification	Dry	Wet	-	-	Dry	Dry	Wet	-

+Survival water applied

APPENDIX 6.2.4

Rainfall (mm) and season classification HATCLIFFE

Month	Season							Mean 1968-74
	1968+	1969+	1970	1971	1972	1973	1974	
Oct.	0	107	3	28	55	35	8	33,7
Nov.	106	28	211	137	66	200	148	128,0
Dec.	154	414	108	173	83	302	210	206,3
Jan.	279	156	173	260	114	144	73	171,3
Feb.	68	56	131	136	90	317	308	158,0
Mar.	124	35	40	121	98	160	80	94,0
April	106	55	13	132	15	44	55	60,0
Total	837	851	679	987	521	1202	882	851,3

+No rainfall records available for Hatcliffe for these years, figures presented are the means of Domboshawa and Salisbury Research Station.

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